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PROGRESS AND PROBLEMS IN THE NORTH AMERICAN PLEISTOCENE[1]

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ABSTRACT

The basic information on North American glaciation that has been gained during the last fifty years is briefly reviewed. In recent years special progress has been made in correlating glacial events with fluctuations of sea-level, in understanding the crustal warping caused by glacial loading and unloading, and in improving our timetable of the later Pleistocene by means of organic, chiefly botanical, evidence.

One of the important tasks that face us now is to explain the location and mode of origin of the great Pleistocene ice sheets in the Northern Hemisphere. It is suggested that these ice caps did not grow up *in situ* but were immigrant, having gradually evolved from valley glaciers in Arctic highlands that stood east of them.

Rapid further progress in Pleistocene stratigraphy will depend more than ever on planned, co-ordinated effort by groups that include scientific workers other than geologists. Such planning should be put into effect at once.

INTRODUCTION

We meet today under the auspices of three organizations, to each of which we have appropriate ties. That a symposium in glacial geology should be among the events that mark the fiftieth anniversary of the University of Chicago is appropriate because from its founding the university has taken a leading place in the study of glacial problems. The Geological Society has always shown the most cordial interest in glacial research, and since its rise to affluence it has granted substantial sums for the furtherance of glacial studies.

[1] Address delivered at Fiftieth Anniversary Celebration of the University of Chicago, September, 1941.

The vice-president and chairman of Section E of the American Association for the Advancement of Science, who is our presiding officer today, is head of the organization that not only is the greatest of our state geological surveys but also has accomplished incomparably more in the field of glacial geology than has any similar organization.

Very largely because of these auspices, it has been possible to gather together today an impressive array of students of glaciation. It is my hope, and the hope of others equally interested in glacial research, that this conference will be followed by many meetings which will bring active glacial geologists closer together than ever before and which, through the free discussion of common problems, will stimulate and, what is more important, co-ordinate our researches, so that by wisely integrated effort we can hope to solve the problems that still confront us.

Meanwhile it seems desirable that we should take stock of what has been accomplished in North America during the remarkable fifty-year history of the University of Chicago—a span that embraces, not altogether without coincidence, the era during which the majority of the great discoveries in North American glacial geology have been made. Therefore let us review past accomplishments, examine our present position, and look at the chief problems that face us.

Recognition and discussion of these problems have been facilitated by the organization of the Committee on Glacial Map of North America. Set up by the National Research Council in October, 1939, this committee is charged with the task of co-ordinating our present knowledge of areal glacial geology and glacial stratigraphy in map form. The committee has formulated sixteen specific field projects, of which seven have been carried out wholly or partly during the field season just ended. These results are exactly what had been hoped for when the map project was launched; there is reason to believe that the research effort has settled down to a steady drive with impetus to carry it forward for many years.

GLACIAL EROSION AND GLACIAL DEPOSITS

From the long controversy on the effectiveness of glaciers as erosive agents we have come at last to realize that the mechanical

principles that govern the work of glaciers are much the same as those that guide the work of streams and consequently that glaciers work very differently in different environments. We now accept as true that rapidly flowing glaciers confined to narrow valleys may, like swift mountain streams, cut deeply, whereas broad ice sheets flowing slowly on irregular floors, under the influence of the differential pressures set up by the slopes of the upper surfaces of the glaciers, may, like the overflow water of a stream in flood, cut far less deeply. Evidence is accumulating that the average depth of glacial erosion in the Canadian Shield is smaller than was formerly believed. Dr. Demorest's deductive treatment of glacier flow[2] is an important contribution to the principles that underlie these differences.

We are beginning to understand, too, from the preservation of thick bodies of older drifts beneath younger, that compact till is a material highly resistant to glacial erosion, that a rock such as closely jointed granite is a much weaker material, and that glacial quarrying or plucking accounts for the removal of much more rock than does glacial abrasion.

Again, the former rigidity in our mechanical classification of drift is disappearing in favor of the realization that a complete gradation exists from ideal ice-laid deposits to ideal water-laid deposits. Still further, the fact that at least some tills have a systematically organized fabric, first demonstrated in Europe, has been clearly shown recently by C. D. Holmes. Study of till fabrics is sure to yield important information on the mechanics of deposition of glacial debris and on the directions of flow of former glaciers in specific districts where more obvious kinds of evidence are lacking.

STRATIGRAPHY

Multiple glaciation in North America was first firmly established by T. C. Chamberlin and R. D. Salisbury in 1893. Since that time, through the classical work of Frank Leverett and others, a standard section has been worked out in the Mississippi Basin region, implying four distinct glaciations, though the fourfold concept is not yet universally accepted. The greatest single problem in the standard sec-

[2] "Glacier Regimens and Ice Movement within Glaciers," *Amer. Jour. Sci.*, Vol. CCXL (1942), pp. 31–66.

tion of this standard region concerns the correlation of the Iowan drift.

Does this fourfold standard section represent all the Pleistocene glacial invasions of northern United States? Throughout most of the drift-border zone in North America east of the Rockies, the younger drift sheets extend less far south than the older ones, in offlapping relationship. It seems unlikely that the climatic fluctuations responsible for these drift sheets began suddenly with the most extensive of them. It is interesting to speculate whether there may not have been less extensive pre-Nebraskan glaciations whose drift sheets have been concealed or destroyed.

Whether or not there were more than four glacial invasions, greater refinement in the study of the ages of the already-recognized drift sheets is much needed, and in this direction we are getting valuable aid from the techniques of the soil scientists. So many variable factors are involved in the development of soil profiles that detailed study of wide areas is necessary before sweeping conclusions can be safely drawn.

Substages, of probably only a few thousand years' duration, have been clearly recognized in the Wisconsin drift; substages can never be widely recognized in the pre-Wisconsin drift, but it is not too much to hope that local subdivision of these drifts may be made.

While our attempts to subdivide the North American glacial stages are going forward, attempts at correlating the North American drift sheets with those of other continents are stimulating and very desirable. Interesting comparisons between North America and Europe have been made on both sides of the Atlantic, and before long a summary of what is known about the glacial stratigraphy of South America east of the Andes will be made available to us for the first time through the effort of Sr. José R. Guiñazú of Buenos Aires. But without belittling in any way the desirability of intercontinental correlations, I think there is much to be said in favor of coming to full agreement on our own glacial succession without allowing ourselves to be influenced unduly by what may be present on other continents. By all means let us look eastward and southward from time to time, but let us first judge our own stratigraphy, as far as possible, on its own merits. Quite aside from the regional differences to be

expected, there is always the possibility that the men across the Atlantic and below the Equator may be wrong. Later, if we are lucky, the Piggot gun on the deep-sea floor may furnish us with the data for unquestioned correlation.

Up to now we have devoted too little attention to the interglacial times and to the time since the last ice sheets disappeared from North America. It is my impression that we think we know more about the interglacials than we do. Actually, only the deposits at Toronto demonstrate an interglacial climate warmer than the present one. Many of the other occurrences of so-called "interglacial" deposits are very unsatisfactory; they hardly do more than show that glacier ice was not upon the immediate site at the time of deposition. We need the fuller application of the techniques of plant ecology—especially pollen analysis—that have been successfully applied to "postglacial" deposits, in order to get a better picture of the climates of the interglacial times and of the broad pattern of climatic fluctuations during the Ice Age. Dr. W. S. Cooper, in a companion paper,[3] summarizes what has been done and what is being done in this field, in which North America is now beginning to catch up with the Europeans, especially the Scandinavians.

Other studies will make additional contributions to our knowledge of climatic fluctuations. One such study concerns the loess sheets. I need do no more than mention these, because Dr. E. T. Apfel[4] will summarize in a separate paper what has been learned about them and—more important—the things we do not yet know, but need to know, about them.

Other significant avenues of attack on climatic fluctuations lie entirely outside the glaciated region. The sequence of major cuts and fills made by large streams during alternate glacial and interglacial times and the sequence of lake deposits (including saline precipitates) and interlake features in the basins of the now arid Southwest offer a rich field of investigation. In the arid country our knowledge is so slight that we are not even certain as to the time relations between the pluvial episodes in extra-glacial regions and the glacial

[3] To be published in the *Journal of Geology*.

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maxima. Solifluction in the surficial mantle under rigorous glacial climates beyond the glaciers themselves, already widely recognized in France and in Britain, has begun to be recognized here and, when fully interpreted, should prove a valuable aid in climatic correlation.

While we are dealing with stratigraphy we must not forget the large part that paleontology must play in our research program. For example, the animal ecology of the Ice Age furnishes its own climatic puzzles, especially in the history of the mammals. In Europe, where the vertebrate record is much less incomplete than in North America —I say "less incomplete" rather than "more complete" advisedly— a whole series of Pliocene warm-climate animals (horses, rhinos, elephants, and carnivores) survived through the first glacial and the first interglacial and then became extinct. A series of new cold-climate forms, including the reindeer, appeared in the second interglacial; while mammals such as the woolly mammoth and woolly rhino, apparently best adapted to conditions of extreme cold, did not appear until the fourth glacial, a time when the glaciers were less extensive than in the preceding glacial maxima. The biggest faunal changes thus occurred not with the first appearance of glaciation but far on in the Ice Age.

In spite of the very imperfect North American record, we find a parallel in the presence of numerous horses, camels, edentates, tapirs, and sabertooth cats early in the Ice Age. Before Wisconsin time the camel and horse had become extinct and the other forms had become greatly reduced in number, and such forms as elephants and bison had become common. The woolly mammoth might have been expected to disappear, as it did, with the last ice sheets, but why such forms as *Archidiskodon* and *Parelephas* should have survived the Ice Age only to become extinct the day before yesterday is a thing no one has satisfactorily explained. Such facts must be kept in mind while we are working on the succession of Ice Age climates.

Continued Pleistocene climatic fluctuation is strikingly demonstrated by the postglacial Climatic Optimum of several thousand years ago, recognized first in Europe and more recently in North America. Still more recently—in fact, currently—data supporting the belief in a "Little Ice Age" beginning only a few thousand years ago in North America have been assembled by Matthes and will be

offered by him in a later paper.[5] Matthes' recognition of this climatic deterioration is important both because it harmonizes with the climatic record of the last several thousand years in Europe, including the Climatic Optimum, and because it is therefore one of the best evidences we yet possess that major climatic changes were nearly simultaneous on both sides of the Atlantic. If a similar "Little Ice Age" could be recognized in South America and approximately dated, it would do away with those hypotheses of the cause of glaciation that demand climatic alternations between the Northern and Southern hemispheres for late Pleistocene time and would strongly imply their inapplicability to Pleistocene time as a whole. One of the objectives of all stratigraphers is a reconstruction of the climatic history of the earth. In this field glacial stratigraphy can be of great service because far more glacial than preglacial evidence is preserved for study. A thorough knowledge of the late Cenozoic climatic changes will surely throw light on the climates of Mesozoic and even Paleozoic times.

STRATIGRAPHIC TERMINOLOGY

Terminology is not a basic matter; it is only a tool. Yet it is essential that we have a commonly accepted currency of terms to enable us to communicate with one another clearly and easily. An unfortunately large number of terms in glacial geology lack widely accepted definitions. That lack will have to be remedied by concerted effort.

The separation of glacial time into major units called "ages," represented by corresponding groups of deposits called "stages," first clearly proposed by J. E. Eaton,[6] seems to have met general acceptance. It is my opinion that this usage should be adopted as standard, with the further addition of the terms "subage" and "substage" to denote major recognizable subdivisions of ages and stages, such as have already been recognized in the Wisconsin.

The delineation of glacial time as a whole is a more difficult matter, partly because, instead of being peculiar to glacial stratigraphy,

[5] To be published in *Science*.

[6] "Divisions and Duration of the Pleistocene in Southern California," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XII (1928), pp. 111–41.

this delimitation must be acceptable to stratigraphers in general and must fit comfortably into the geologic column as a whole. Time prevents the treatment here that this important matter deserves. However, I should like to voice an opinion on it, if only to provide a solid bone of contention, for we glacial geologists must discuss the problem thoroughly and must try to reach an agreement so that we all shall know what we are talking about. I agree with Charles Schuchert and C. O. Dunbar[7] that the terms "Tertiary" and "Quaternary" are undesirable, because they are based on outmoded concepts, and should be dropped just as the terms "Primary" and "Secondary," parts of the same classification, were dropped. I fear that "Tertiary" is well entrenched in common use, but "Quaternary" is not—it is used chiefly in a rather formal way in paper classifications. As used by the United States Geological Survey, it includes "Pleistocene" and "Recent"; yet the distinction between these two terms is artificial. As our knowledge grows and as we are able to fill in more and more completely the steps in the transition from glacial occupation to modern conditions in any one region, we see clearly that terms such as Lyell's "Recent" and "postglacial" apply only to specific localities and have little if any general significance. Especially is this true when we realize that one-tenth of the land area of the world is still covered by glacier ice, a condition that is not "postglacial" or, as far as we know, characteristic of preglacial time. Furthermore, it is certain that the interglacial ages have been far longer than so-called "postglacial" time, and that in one of them, at least, the earth has been freer of glaciers than it is at present. It is true, of course, that the encroachment and regression of any Paleozoic sea was, like the expansion of the glaciers, a gradual and progressive event and that the time unit represented by the deposits in that sea began much earlier in some places than in others. But in most cases the evidence of such events is so scanty that it is sufficient to recognize the fact and to accept the corresponding unconformity as marking the beginning of the corresponding stratigraphic unit. It may indeed be necessary to follow just this convention with the somewhat obscure *beginning* of glacial time, but we have so detailed a record of the past

[7] *A Textbook of Geology*, Part II: *Historical Geology* (4th ed.; New York: John Wiley & Sons, 1941), pp. 383–84, 425.

few millenniums that it seems unnecessary and artificial to follow such a convention there.

I therefore suggest, tentatively and for purposes of discussion, that we try to forget the term "Quaternary" and define the Pleistocene epoch so as to include the so-called "Recent" and then, as knowledge grows, add further subages to the last glacial age if they are needed.

The Pleistocene or the so-called "Quaternary" has been delimited by no means either exclusively or universally on a basis of glaciation. Other bases of delimitation that have been proposed include (1) molluscan fauna, (2) mammalian fauna, (3) eustatic fluctuation of sea-level, (4) world-wide temperature changes, both atmospheric and oceanic, (5) conspicuous stream trenching, and even (6) the biblical Flood. I suggest that the basis sanctioned by the United States Geological Survey—that of "the deposits of the Great Ice Age . . . . , and contemporaneous marine, fluviatile, lacustrine, and volcanic rocks"[8]—is the one we should adhere to, because *glaciation* is the outstanding and most easily recognizable fact in this bracket of time and because even in nonglaciated regions the climatic changes that accompanied glaciation were great enough in large areas of the world to influence terrestrial stratigraphy and land forms, sea-level fluctuations, and even marine ecology, and thus to afford a correlative basis of recognition. According to this view, the important factors are glaciation and the strong climatic changes that accompanied glaciation.

DELEVELING

The present century has witnessed the development of almost the whole of our knowledge of Pleistocene deleveling, including both (1) crustal warping by glacial loading and unloading as the great glaciers waxed and waned and (2) eustatic fluctuations of sea-level by remote control as the glaciers piled up moisture on the lands and then returned it to the sea. These factors, together with the effects of local crustal warping entirely unconnected with glacial loads—such as is clearly demonstrated in coastal California and in the Mediterranean region—combine to create a very complex picture.

[8] M. G. Wilmarth, "The Geologic Time Classification of the United States Geological Survey . . . . ," *U.S. Geol. Surv. Bull. 769* (1925), p. 49.

The best reconstruction we shall ever be able to make of crustal responses to the weight of the glaciers will be very incomplete because reconstructions require the presence of warped features (marine and lacustrine strand-lines) that can be shown to have been originally horizontal. The detailed work of Gilbert, Taylor, Upham, and others has shown us what can be done. We must continue this work, reconstructing from whatever evidence is offered, with the knowledge that very large areal gaps will always exist. Such work is important not only as a basis for inferring the weights and volumes of the vanished glaciers of the last glacial age but as a contribution to the solution of problems that confront structural geologists. B. Gutenberg[9] has recently brought together data that suggest that the uplift still to be expected before equilibrium is restored, in both North America and Fennoscandia, is of the order of 600 feet. The future geographic changes implied by this figure are surprising. They include the emergence of the whole of the Gulf of Bothnia and of all of Hudson Bay excepting part of the narrow submerged valley that leads into Hudson Strait—a valley that was very probably the preglacial continuation of the Missouri River system in North Dakota and Montana before the great glacial blocking and diversion occurred.

In comparison with crustal warping, we have a much better chance of reconstructing the eustatic fluctuations of sea-level, because the evidence is more widely distributed and is less incomplete. Dr. MacClintock, who has been concerned with this problem for several years, will shortly discuss it for our benefit. However, I should like to make two or three general statements now: The critical evidence lies both above and below sea-level. Below sea-level, closely spaced accurate sounding surveys such as those carried out by the United States Coast and Geodetic Survey off the Atlantic Coast of the United States have revealed the presence, according to the interpretations of Veatch and Smith, of a warped strand-line at depths of 240–330 feet. When this program of sounding on the continental shelves is extended, we are very likely to gain further information about the low sea-levels of the glacial ages. Excavations

[9] "Changes in Sea Level, Postglacial Uplift, and Mobility of the Earth's Interior," *Bull. Geol. Soc. Amer.*, Vol. LII (1941), p. 751.

and deep borings along coasts will amplify such information. Above sea-level former strand-line features are best seen in nonglaciated, crustally quiescent regions of weak rocks—the regions most nearly free from complicating outside influences. Our own Atlantic Coastal Plain, islands such as Bermuda, and the east coast of South America, generally, possess these advantages. Both our own east coast and the island of Bermuda have already yielded some results.

One of the impressive results of R. W. Sayles's excellent study of Bermuda[10] concerns the platform, 1–3 miles wide and submerged to a depth of 70 feet, that surrounds the island proper and apparently cuts Pleistocene strata. Sayles recognized this platform as the record of a prolonged halt of sea-level at about this level. In 1940 I described a conspicuous wave-cut bench up to more than 200 feet in width, transecting bedrock in western Newfoundland. I showed that it postdated the last glaciation, described it as the only feature yet observed (other than the similar wave-cut bench at present sea-level) that records a prolonged halt in the postglacial rise of sea-level, and estimated possibly five thousand years as the time necessary for its production. I suggest that this Newfoundland surface and the Bermuda platform may have been cut at the same time (a time which may perhaps deserve recognition as a subage), just before the sea-level accomplished its last rise of about 70 feet. The fact that the Newfoundland bench is warped, rising northward from below sea-level to altitudes of at least 250 feet above sea-level, is the result of crustal warping by glacial unloading that did not, of course, affect Bermuda. If the full width of the Bermuda platform had been cut in the time required for the cutting of the Newfoundland bench, then the rate of cutting of the Bermuda calcareous eolianites by Atlantic waves must have been twenty-five to seventy-five times as rapid as the rate of cutting of the Paleozoic sedimentary rocks and serpentinized peridotite in Newfoundland by the lesser waves of the Gulf of St. Lawrence. Whether such a ratio is probable is a matter for argument.

If there is any merit in this suggestion, the very late Pleistocene record of other parts of North America likewise should indicate a cor-

[10] "Bermuda during the Ice Age," *Proc. Amer. Acad. Arts and Sci.*, Vol. LXVI (1931), pp. 381–467.

responding pause of the same order of magnitude. In E. Antevs' correlation of events in the Great Lakes region[11] we find just such a record—the record of a time of crustal quiescence lasting five thousand years—in the Lake Algonquin subage and dating, according to Antevs' chronology, from twenty-one thousand to sixteen thousand years ago. Crustal quiescence presumably means ice sheets approximately in equilibrium, with little net wastage or accumulation, and this in turn means, in terms of glacial control, a stable sea-level in which marine benching can take place. If we accept Antevs' figures, perhaps we have a correlation of the Newfoundland or Bermuda features, or both, with the time of Lake Algonquin. Whether or not this is substantiated later, I am sure that we have or shall have the facts upon which broad correlations can be made and upon which we can therefore add much to our timetable of late Pleistocene events.

CAUSES OF GLACIATION AND GENESIS OF ICE SHEETS

One of the great objectives of glacial study is the understanding of the causes of widespread glaciation. Much thought, chiefly deductive in character, has been given to the problem, and among the results probably lie the germs of the truth. Yet we are still a long way from this goal, chiefly because we have been working with a great insufficiency of data and have thus been unable definitely to discard any one hypothesis. The significant facts will come chiefly from studies of the economy (including the meteorology) of existing glaciers, especially ice sheets. During the last ten years Ahlmann and his associates have accomplished first-rate pioneer work in this field on relatively small ice sheets in Norway, Iceland, and Spitsbergen. If a co-ordinated program of parallel studies can be carried out over a period of years on the much larger ice sheets of Greenland and Antarctica, the resulting data should enable us to reduce the number of our hypotheses on the causes of glaciation.

The fact that the majority of present and past glaciers are closely related to mountains and other highlands was recognized by Dana eighty-five years ago and led to what was, as far as I can discover, the earliest scientific hypothesis of the cause of glaciation, namely,

[11] "Late Quaternary Upwarpings of North America," *Jour. Geol.*, Vol. XLVII (1939), p. 719.

that *elevation* of parts of the earth's crust was the responsible factor. When, many years later, this very reasonable idea met the indisputable evidence of multiple glaciation discovered by Newberry, Orton, Winchell, McGee, Chamberlin, and Salisbury, it fell quickly into disfavor because of the absurdity of the implication that the land had gone up and down repeatedly during the Pleistocene. The Croll hypothesis, involving extra-terrestrial factors, was then enthusiastically received in its place. Croll's idea has long since been seen to involve great difficulties, and, though we may reject it as a whole, just as Dana's idea was rejected as a whole, we may well draw the helpful concept from a review of Croll's and Dana's thinking that the peculiar climatic conditions of the Pleistocene are polygenetic; that they are the result partly of topographic factors and partly of extra-terrestrial influences. The successive glacial and interglacial ages of the Pleistocene, not to mention the "Little Ice Age" of very recent time, occurred without any notable changes in altitude, ocean currents, or areal relations of land to sea. These changing ages must indeed have been the result of climatic fluctuation motivated by factors outside the earth. Yet such fluctuations appear to have occurred repeatedly throughout geologic time, without having left a record of widespread glaciation other than in the Permian and the Upper pre-Cambrian. Our knowledge of the Upper pre-Cambrian is too scanty for an opinion, but the Permian and the late Cenozoic are clearly associated with extensive highlands. The important and stimulating paper by R. W. Chaney on "Tertiary Forests and Continental History"[12] not only shows that the climatic belts in the Northern Hemisphere, although they have shifted position somewhat, have remained in the same relative positions since Eocene time, but also emphasizes on floral evidence our growing realization that post-Miocene–Cenozoic time witnessed a very great increase in the relief of North America. We therefore ought to give thought to the hypothesis that climatic fluctuations motivated from outside the earth may have occurred repeatedly throughout geologic time, that in times of low lands and extensive seas (the Ordovician and the Cretaceous periods are extreme examples) cooling was minimized, but that cooling coinciding with a time of high lands, such as the late

[12] *Bull. Geol. Soc. Amer.*, Vol. LI (1940), pp. 469–88.

Cenozoic, was enhanced and implemented so as to cause glaciation in high latitudes and at high altitudes.

This general idea, which certainly must have been widely entertained though it has not been much discussed, seems to stand in opposition to the fact that some of the chief "centers of glaciation" in the Northern Hemisphere occupied not high land but low land and stood in areas not of large precipitation but of moderate or small precipitation. Thus it leads us directly to the problem of the genesis of an ice sheet. Much speculation has been indulged in concerning the factors behind this apparently anomalous location of the "ice centers," and very drastic climatic changes have been invoked for the production of the precipitation requisite for building these ice sheets. Yet, it seems to me, the notion that the Labrador, Keewatin, and Scandinavian ice sheets grew up *as ice sheets in situ* is meteorologically unsound. If we consider the hypothesis that these glaciers did not form *in situ*, but were intrusive or immigrant from places where glaciers could form without being meteorological anomalies, the difficulties disappear. Today in Spitsbergen and in Alaska we find existing gradations from valley glaciers through piedmont glaciers to ice sheets. Why should not such gradations have occurred in the past?

Although a somewhat similar "ice center" has long been recognized near the head of the Gulf of Bothnia, it is well understood by Fennoscandian geologists that the last European ice sheet did not originate here. The ice sheet is generally regarded as having begun as an extensive series of valley glaciers fed by moist westerly winds from the Atlantic, on the high mountains that form the Swedish-Norwegian watershed. The accumulation of ice became so great that the valley glaciers coalesced to form piedmont glaciers and finally an ice sheet. This vast accumulation swamped the mountains, and became semi-independent of them, somewhat as a sand dune grows independent of the obstacle that originally caused it to take form. Its center shifted east, locally reversing the direction of flow so that, at the glacial maximum, ice originating over the Gulf of Bothnia flowed westward *across* the mountains to the Atlantic.

Partly along the line suggested by F. Leverett,[13] a similar explanation can be applied to the North American ice, if we consider the

[13] "Pleistocene Deposits of Minnesota and Adjacent Districts" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. XXVII (1916), p. 68.

mountains of the Coast of Labrador, whose summits reach well over 4,000 feet (and perhaps also the highlands of extreme eastern Quebec), and the higher and more extensive mountains of Baffin Island, as the initial snow-catchers, the sites of the earliest small glaciers. Picture the valley glaciers as growing into piedmonts and as expanding southwestward in the direction of the moisture-bringing planetary winds.[14] Picture the ice as thickening until it swamped the coastal mountains, forming successive centers of outflow independent of the mountains, setting up "glacial anticyclones" over its surface, and occupying virtually the whole vast area of Canada east of the Cordillera as well as much of the United States.

Shifts in the positions of the Keewatin and Labradorian "centers" amounting to several hundred miles are clearly recorded by the observations of Tyrrell and Low, though all but a few of the observed striations record only the latest directions of flow.

In Greenland today we are witnessing a waning episode in the history of a large ice sheet that formerly covered or nearly covered the coastal mountains of that island. The ice sheet is thinning, planetary cyclonic storms are challenging the strength of the "glacial anticyclone," and valley glaciers are re-establishing themselves on the emerging mountain ranges. If the present climatic trend were to continue long enough, we could look forward to a time when Greenland's interior would be ice free and only the higher mountains would have glaciers.

With our present very incomplete knowledge, we can perhaps say little more for the concept that the North American ice east of the Cordillera originated principally in the highlands of the coast of Labrador and Baffin Island than that it appears to make sense meteorologically.

ARCTIC GLACIAL RESEARCH

In this problem of ice-sheet origin as well as in the general areal glacial geology of North America, arctic glacial research is highly important. Yet arctic research has been grossly neglected. The body of glacial data on the North American arctic is pitifully small, and nearly all this information is the by-product of reconnaissance

[14] T. C. Chamberlin and R. D. Salisbury (*Geology*, Vol. III [New York: Henry Holt & Co., 1906], p. 333) were the first to point out the windward direction of expansion of the North American ice sheets.

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Partly along the line suggested by F. Leverett,[13] a similar explanation can be applied to the North American ice, if we consider the

[13] "Pleistocene Deposits of Minnesota and Adjacent Districts" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. XXVII (1916), p. 68.

mountains of the Coast of Labrador, whose summits reach well over 4,000 feet (and perhaps also the highlands of extreme eastern Quebec), and the higher and more extensive mountains of Baffin Island, as the initial snow-catchers, the sites of the earliest small glaciers. Picture the valley glaciers as growing into piedmonts and as expanding southwestward in the direction of the moisture-bringing planetary winds.[14] Picture the ice as thickening until it swamped the coastal mountains, forming successive centers of outflow independent of the mountains, setting up "glacial anticyclones" over its surface, and occupying virtually the whole vast area of Canada east of the Cordillera as well as much of the United States.

Shifts in the positions of the Keewatin and Labradorian "centers" amounting to several hundred miles are clearly recorded by the observations of Tyrrell and Low, though all but a few of the observed striations record only the latest directions of flow.

In Greenland today we are witnessing a waning episode in the history of a large ice sheet that formerly covered or nearly covered the coastal mountains of that island. The ice sheet is thinning, planetary cyclonic storms are challenging the strength of the "glacial anticyclone," and valley glaciers are re-establishing themselves on the emerging mountain ranges. If the present climatic trend were to continue long enough, we could look forward to a time when Greenland's interior would be ice free and only the higher mountains would have glaciers.

With our present very incomplete knowledge, we can perhaps say little more for the concept that the North American ice east of the Cordillera originated principally in the highlands of the coast of Labrador and Baffin Island than that it appears to make sense meteorologically.

ARCTIC GLACIAL RESEARCH

In this problem of ice-sheet origin as well as in the general areal glacial geology of North America, arctic glacial research is highly important. Yet arctic research has been grossly neglected. The body of glacial data on the North American arctic is pitifully small, and nearly all this information is the by-product of reconnaissance

[14] T. C. Chamberlin and R. D. Salisbury (*Geology*, Vol. III [New York: Henry Holt & Co., 1906], p. 333) were the first to point out the windward direction of expansion of the North American ice sheets.

examination of the bedrocks. Very few trained glacial geologists have made studies in our arctic regions. The excellent work of Capps in Alaska is an exception, but a large proportion of even his glacial results were the by-product of other work. Yet in the arctic fringe of North America we have a glaciated sector almost as long as the much-studied southern drift-border zone between New York and the Rocky Mountains. Until this huge gap has been plugged with glacial information, our efforts to arrive at a well-rounded understanding of North American glaciation are stopped.

Now, fortunately, this situation is beginning to change. A new, direct attack is exemplified by the work begun by A. L. Washburn, which he hopes to extend over a much larger region. Other North American arctic glacial projects are on foot, and I sincerely hope their execution will not be indefinitely delayed by the war.

CONCLUSION

In any review of accomplishments in a given sector of knowledge and in any look along the frontiers of knowledge in that sector, the conclusion is always obvious that we need much more information and that we need it most in certain specific directions. What I want to emphasize is the somewhat less obvious point that we shall acquire the facts we are seeking much more quickly and efficiently if we organize and co-ordinate our attack. The solution of some of our most important glacial problems depends on the findings, not only of geologists, but of botanists, zoölogists, physicists, soil scientists, meteorologists, and oceanographers. For the most part the men in these fields are working outward from centers in their own disciplines and find it difficult to make contact with workers moving toward them from centers in adjacent disciplines. Integration of the efforts of these workers is essential. Perhaps we need some organization, some co-ordinating agency, through which problems can be defined and then efficiently approached from two or more directions at once. When the need for formal organization is felt acutely enough, I feel sure it will come into existence.

Meanwhile we are able to look back on half a century of admirable progress, the results of which only serve to stimulate our efforts to extend the frontiers of our knowledge.

DIFFERENTIATION OF THE DOLERITES OF TASMANIA. II*

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MINERALOGY

The Tasmanian dolerites consist essentially of pyroxenes and basic plagioclase, with small amounts of interstitial quartz and alkali feldspars, generally in micrographic intergrowths with one another. Olivine is occasionally present in small quantities, and chlorite is present in some sections as an alteration product of the ferromagnesians. Accessory minerals include biotite, iron ore, and occasionally pyrite.

The dolerites have a finely intergranular texture in their chilled portions, with a tendency, noted by Twelvetrees,[38] for the earliest-formed pyroxenes to occur as phenocrysts. Toward the central portions of the dolerite sills there is a progressive change to a coarse ophitic texture, which is accompanied by an increase in the proportion of interstitial alkali feldspar. The change in grain size in the Mount Wellington sill, which is typical, is shown in Table 9. The figures recorded refer to the largest crystals of plagioclase and pyroxene observed in the sections examined. Examination of the chilled top preserved on Mount Nelson indicates that a rather more rapid return to a fine-grained intergranular texture took place in the eroded part of the sill that existed above the coarse-grained acid phase now forming the summit of Mount Wellington.

In the large dikes (as represented by Gunning's Sugarloaf) the increase in grain size is not so marked, particularly in the case of the plagioclase laths, nor is the ophitic texture so strongly developed. The pyroxenes tend, instead, toward a glomeroporphyritic structure.

1. OLIVINE

Olivine is an uncommon mineral in the Tasmanian dolerites. Twelvetrees and Petterd[39] noted its sporadic occurrence as one of the

* Continued from p. 480.

[38] "On the Nomenclature . . . . ," *op. cit.*, p. 290.

[39] "On Mesozoic . . . . ," *op. cit.*, p. 50.

earliest-formed minerals in the dolerite at several localities in eastern Tasmania and classed it as an "accessory" mineral. During the present investigation it has been found only in the chilled base of the Mount Sedgwick laccolith, where it occurs as corroded microphenocrysts about 0.5 mm. in diameter, sparsely scattered through the fine groundmass. A number of the olivine grains are enclosed by early-formed pyroxene, so that the olivine was the first mineral to crystallize and had begun to dissolve again by the time that crystal-

TABLE 9

VARIATION IN GRAIN SIZE IN THE MOUNT WELLINGTON SILL

Elevation above Sea-Level (Feet)	Plagioclase (Sq. Mm., Maximum)	Pyroxene (Sq. Mm., Maximum)
4,150 (summit)	1.51	4.05
4,000	1.40	3.43
3,850	0.90	4.05
3,700	0.50	2.45
3,550	0.74	1.62
3,450	0.31	1.47
3,400	0.35	0.61
3,275	0.10	0.50
3,150	0.06	0.15
3,125 (base)	0.03	0.07

lization of the pyroxene commenced. Occasional remnants of similar olivine crystals are found higher in the laccolith. The olivine has a $(-)2V = 85°–90°$, indicating that its composition is about $Fo_{87}Fa_{13}$.

2. PLAGIOCLASE

Calcic plagioclase is the dominant feldspar in the dolerites and is lathlike to tabular in form. It is commonly zoned, and extinction angles show that the range in composition is usually from bytownite (An_{75}) in the core to basic oligoclase (An_{26}) in the outer zone. The oligoclase margins are usually very thin. Many crystals show five zones, each differing in composition from the next inmost by about 10 per cent of anorthite. Occasional crystals show six zones with a core of a composition bordering on anorthite (An_{90}). A slight increase in the soda content of the core zones is noted in the higher

levels of sills like Mount Wellington and Mount Nelson, the most soda-rich cores having the composition of labradorite (An_{60}–An_{65}). This is confirmed by optical measurements with a universal stage kindly made by Dr. F. J. Turner, of Otago University, on slides from the summit of Mount Wellington. A section showing a Carlsbad twin had $(+ve)2V = 82°$ and extinction angles $(001)\alpha = 37.5°$, $(001)\beta = 73°$, $(001)\gamma = 58°$.

In the sills the proportion of plagioclase decreases from about 45 per cent at the chilled base to about 35 per cent in the magnesia-rich layer and then increases rapidly again to about 55–60 per cent. In the Mount Wellington sill it reaches a maximum of about 65 per cent at about 200 feet below the present summit and then decreases to about 55 per cent at the summit, which corresponds with the form of the Na_2O profile (Fig. 8). In the dike the proportion of plagioclase increases steadily as one progresses from the chilled margin toward the central portions of the dike.

3. PYROXENES

Three distinct series of pyroxenes—augites, orthopyroxenes, and pigeonites (enstatite-augites)—occur in the Tasmanian dolerites, as noted by Twelvetrees and Petterd[40] and Osann.[41] The association of all three in a single intrusion was first recorded by Benson[42] at Cradle Mountain.

The chemical analyses of individual sills or dikes and of the dolerites as a whole show that there is a general trend for the later-formed pyroxenes to be richer in FeO and poorer in MgO than the earlier-formed ones. This may be seen from Figure 13, in which the ratio FeO:MgO is plotted against MgO content for all the available analyses of Tasmanian dolerites. The FeO:MgO ratio ranges from 0.8 in the most basic phases to 6.1 in the most acid, and the rate of increase accelerates as the MgO content of the rocks decreases. Since both the FeO and the MgO must occur chiefly in the pyroxenes, it follows that Figure 13 represents the general trend of composition change in the pyroxenes as differentiation progressed.

[40] "On Mesozoic . . . . ," *op. cit.*, p. 50; Twelvetrees, "On the Nomenclature . . . . ," *op. cit.*, p. 290.

[41] *Op. cit.* [42] "Notes on the Geology . . . . ," *op. cit.*, p. 33.

This is confirmed by chemical analyses of the pyroxene constituents of the rocks. In Table 10 are shown the analyses of the composite pyroxenes from the chilled contact of the Mount Wellington sill, from more slowly cooled dolerite at Cataract Gorge near Launceston, and from the acid phase at the summit of the Mount Wellington sill.

The samples for analysis from the Mount Wellington sill were obtained by suspending the rock powders used for the complete rock analyses in Clerici solution, when the pyroxenes separated as a

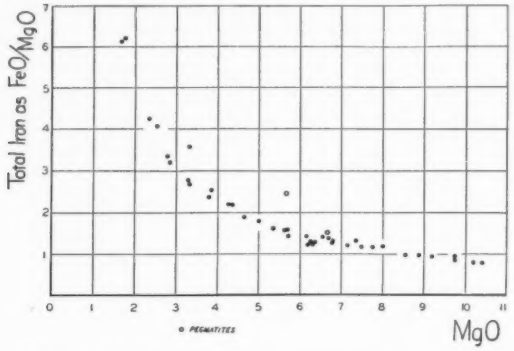

FIG. 13.—Relation of FeO:MgO to MgO-content in the Tasmanian dolerites. The open circles represent pegmatitic segregations of Table 8.

heavy residue. The residues were then re-treated in Clerici solution, and the products were found to be tolerably free from feldspar fragments. Magnetite was removed from the powders with a strong hand magnet; but, owing to the marked tendency of the different pyroxenes to form interlocking growths with one another, it was found impossible to get a clean separation of the individual pyroxenes from one another. Analyses were made, therefore, of the composite pyroxenes, as Osann[43] had been forced to do previously.

The analysis of the pyroxene from the undifferentiated chilled base of the Mount Wellington sill should represent the mean composition of all the pyroxenes in the sills or dikes. As the analyses of Table 10 show, the iron content of this "mean pyroxene" is inter-

[43] *Op. cit.*

mediate between that formed in the more slowly cooled dolerite of Cataract Gorge and that from the acid phase at the summit of the Mount Wellington sill.

The pyroxenes present in the Cataract Gorge rock described by Osann were augite ($2E = 45°$) and pigeonite ($2E = 12°$), and the

TABLE 10

COMPOSITE PYROXENES FROM TASMANIAN DOLERITES

	1	2	3
SiO_2	48.40	51.87	44.05
Al_2O_3	5.25	2.02	4.85
Fe_2O_3	2.49	3.50	4.54
FeO	15.05	8.98	24.91
MgO	14.88	16.26	8.39
CaO	12.70	15.70	12.19
Na_2O	0.10	0.16	0.15
K_2O	0.05	0.09	0.04
H_2O	0.20	1.20	0.12
TiO_2	0.31	0.21	0.60
P_2O_5	tr.	.....	0.03
MnO	0.35	0.18	0.52
Total	99.60	100.17	100.39

1. Composite pyroxene from the chilled base of the Mount Wellington sill (rock analysis, Table 4, No. 1), at the contact. A. B. Edwards, analyst.

2. Composite pyroxene from dolerite at Cataract Gorge, near Launceston (rock analysis, Table 2, No. 1). Dittrich, analyst. (*Centralbl. f. Min. Geol. Pal.*, Vol. XXIII [1907], pp. 705–11; also, *Ann. Rept. Sec. Mines Tasmania* [1908].)

3. Composite pyroxene from acid phase at the summit of Mount Wellington sill (rock analysis, Table 4, No. 10). A. B. Edwards, analyst.

chemical composition of the rock (Table 2, Analysis No. 1) reveals that the rock, though more slowly cooled than the chilled contact rock, had not advanced far along the path of differentiation. The low FeO content and the high MgO content of the composite pyroxenes from this rock (Table 10, Analysis No. 2) show that the early-formed pyroxenes under conditions of relatively slow cooling were magnesia-rich varieties, distinctly richer in MgO and poorer in FeO than the mean pyroxene of the sill. The composite pyroxene from the acid layer at Mount Wellington is, on the other hand, dis-

tinctly richer in FeO and poorer in MgO than the mean pyroxene of the chilled contact. Further proof of this trend from early-formed pyroxenes rich in MgO to later-formed pyroxenes rich in FeO is provided by the optical data that follow.

AUGITE

Augite occurs throughout the sills and dikes, with the exception of the actual chilled contacts. In the lower parts of the sills it is present in amounts equal to, or in excess of, the orthopyroxenes and shows a strong tendency to crystallize as rims around earlier-formed crystals of bronzite. Higher in the sills and in the central parts of the dikes it is associated with pigeonite. Sometimes the augite forms rims enclosing the pigeonite; sometimes the pigeonite encloses the augite; and sometimes the two occur interlocked in composite, allotriomorphic grains. This intimate association is so constant as to leave no doubt as to their simultaneous crystallization.

Measurements of the optic axial angles of the augite in thin sections from different levels in the Mount Wellington sill were made by Dr. Turner on a universal stage and gave the results shown in Table 11. The approximate composition of the pyroxenes at each level in the sill were computed from W. A. Deer and L. R. Wager's[44] diagram of the relationship of $2V$ and $\gamma:c$ to composition; and the average of all the compositions so obtained for any one section was taken as representative. It will be seen from Table 11 that in the lower part of the sill the augite maintains a constant composition but that in the higher layers it grows richer in the $FeSiO_3$. The iron tends to replace magnesium more readily than it replaces calcium. The significance of this is discussed later.

The augite appears colorless throughout, is always optically positive, and has its optic plane parallel to (010). It sometimes shows a pronounced parting parallel to (001) and occasionally parallel to (010) as well and is sometimes twinned on (100). Some crystals are zoned, and, where the $2V$ of the separate zones has been measured, the outer zone has been found richer in iron than the inner zone. In the most iron-rich crystals, from the summit of Mount Wellington, $\gamma - \alpha = 0.025$.

[44] "On Two New Pyroxenes in the Series Diopside-Hedenbergite-Clinoenstatite-Clinoferrosilite," *Min. Mag.*, Vol. XXV (1939), p. 22.

PIGEONITES

Two varieties of pigeonite occur in the dolerite intrusions. One is a metastable form which is present only in the rapidly chilled rock in the immediate vicinity of contacts and is akin to the metastable pigeonites that crystallize in the groundmass of some basalts upon extrusion. This pigeonite occurs in grains too small for its optical

TABLE 11

VARIATION IN OPTICAL PROPERTIES AND COMPOSITION OF AUGITES IN THE MOUNT WELLINGTON SILL

No.	Position in Sill	$2V$	$\gamma : c$	Approximate Composition
6.....	Summit, 1,025 ft. above lower contact	40°–46°	43°–44°	$CaSiO_3$ = 27 $MgSiO_3$ = 48 $FeSiO_3$ = 25
5.....	150 ft. below summit, 875 ft. above lower contact	47°–50° 41° (inner) 47° (outer)	41°	$CaSiO_3$ = 32 $MgSiO_3$ = 53 $FeSiO_3$ = 15
4.....	300 ft. below summit, 725 ft. above lower contact	43°–46°	40°–41°	$CaSiO_3$ = 30 $MgSiO_3$ = 59 $FeSiO_3$ = 11
3.....	450 ft. below summit, 575 ft. above lower contact	46°–50° 62° (inner) 52° (middle) 34° (outer)	36°–38°	$CaSiO_3$ = 36 $MgSiO_3$ = 60 $FeSiO_3$ = 4
2.....	Magnesia-rich layer, 750 ft. below summit, 275 ft. above lower contact	49°–58° 58° (inner) 44° (outer)	39°–41°	$CaSiO_3$ = 36 $MgSiO_3$ = 58 $FeSiO_3$ = 6
1.....	1,005 ft. below summit, 20 ft. above lower contact	46°–50°	38°	$CaSiO_3$ = 35 $MgSiO_3$ = 60 $FeSiO_3$ = 5

characters to be determined satisfactorily; but, since it is accompanied by only a few microphenocrysts of bronzite, its composition must be close to that of the composite pyroxenes from the rapidly chilled rock at the lower contact of the Mount Wellington sill (Table 10, Analysis No. 1) and, therefore, to the mean pyroxene of the dolerite intrusions. If the CaO, MgO, and FeO of the analysis are converted to $CaSiO_3$, $MgSiO_3$, $FeSiO_3$, and recalculated to 100, the composition of this pyroxene may be considered as $CaSiO_3$ = 29,

$MgSiO_3$ = 41, $FeSiO_3$ = 30. The recorded $CaSiO_3$ content may be too high, on account of a small amount of plagioclase not removed from the analyzed powder.

The other pigeonite occurs in the upper parts of the sills, chiefly above the magnesia-rich layers, and in the central parts of the dike-like masses (assuming that Gunning's Sugarloaf is representative of these). For purposes of distinction it may be termed "plutonic" pigeonite,[45] since it crystallized from a slowly cooling magma simul-

TABLE 12

VARIATIONS IN THE OPTICAL PROPERTIES AND COMPOSITION OF PIGEONITE IN THE MOUNT WELLINGTON SILL

No.	Position in Sill	(+) $2V$	$\gamma : c$	Approximate Composition
6.....	Summit, 1,025 ft. above lower contact	17°–22°	38°	$CaSiO_3$ = 10 $MgSiO_3$ = 20 $FeSiO_3$ = 70
5.....	150 ft. below summit, 875 ft. above lower contact	4°–7° 7° (inner) 5° (outer)	41°	$CaSiO_3$ = 10 $MgSiO_3$ = 40 $FeSiO_3$ = 50
4.....	300 ft. below summit, 725 ft. above lower contact	8°	42°	$CaSiO_3$ = 10 $MgSiO_3$ = 50 $FeSiO_3$ = 40
3.....	450 ft. below summit, 575 ft. above lower contact	12°–22°	37°	$CaSiO_3$ = 5 $MgSiO_3$ = 65 $FeSiO_3$ = 30

taneously with augite. As would be expected, this plutonic pigeonite contains much less $CaSiO_3$ than the metastable form. Measurements of the optical properties of this pigeonite in thin sections from different levels of the Mount Wellington sill were made by Dr. Turner. The results are shown in Table 12, together with their approximate compositions, which were derived by averaging the compositions computed from the optical measurements according to Deer and Wager's diagram.[46] They show that the iron content of the plutonic pigeonite increases rapidly in the upper layers of the sill. The axial

[45] Cf. Wager and Deer, *The Petrology of the Skaergaard Intrusion, Kangerdlugssuaq, East Greenland*, "Meddelelser om Grønland," Vol. CV, No. 4 (1939), pp. 242 and 258, nn.

[46] "On Two New Pyroxenes . . . . ," *op. cit.*, p. 22.

angle at first decreases to zero and then increases again. While it is decreasing, the pigeonites have their axial plane normal to (010); but, once it passes zero and begins to increase again, they have their axial plane parallel to (010). The change-over was observed in a single-zoned crystal in the section from 150 feet below the summit (Table 12, No. 5). The central part of the crystal had $2V = 7°$, with the axial plane normal to (010), while the marginal zone had $2V = 5°$, with the axial plane parallel to (010). In the most iron-rich pigeonite $\gamma - \alpha = 0.028$. This pigeonite is colorless throughout and often shows a pronounced parting parallel to (001), which resembles the lamellar structure in the orthopyroxenes. In twinned crystals it

TABLE 13

VARIATION IN OPTICAL PROPERTIES AND COMPOSITION OF ORTHOPYROXENE IN THE MOUNT WELLINGTON SILL

No.	Position in Sill	$2V$	Approximate Composition
2.....	Magnesia-rich layer 275 ft. above lower contact	(−) 65°–78° 80° (center) 70° (margin)	$MgSiO_3 = 70$ $FeSiO_3 = 30$
1.....	20 ft. above the lower contact	(±) 90°	$MgSiO_3 = 85$ $FeSiO_3 = 15$

gives rise to a "herringbone" pattern. No well-defined lamellas of intermixed material can be detected in the partings, however. Frequently the partings do not extend over the whole of the crystal, and, when invaded by alteration products, they give the pyroxene a patchy appearance.

ORTHOPYROXENES

Orthopyroxenes occur, chiefly as microphenocrysts, in the chilled margins of all the sills and dikes examined and in the lower levels of the sills. They appear to be restricted to this distribution, and at higher levels in the sills they give place to stable pigeonite, as noted by Benson[47] at Cradle Mountain. The orthopyroxene was the first mineral other than olivine to crystallize from the dolerite magma. Measurements of the optic axial angles of the orthopyroxenes in thin

[47] "Notes on the Geology . . . . ," *op. cit.*, p. 33.

sections from different levels in the Mount Wellington sill were made by Dr. Turner on the universal stage and gave the results shown in Table 13. The compositions of the orthopyroxenes were computed from N. F. M. Henry's diagram[48] and averaged to give representative figures. They show that the earlier-formed orthopyroxene, close to the lower contact of the sill, has the composition of bronzite, while that formed higher in the sill and collected in the magnesia-rich layer is hypersthene, so that the later-formed orthopyroxenes were enriched in iron relative to magnesium.

Both the bronzite and the hypersthene are colorless and without pleochroism in thin sections of normal thickness. The hypersthene in the magnesia-rich layer of the Mount Wellington sill shows a pronounced lamellar structure, and in twinned crystals this gives rise to a herringbone pattern. In a specimen from about 75 feet below this layer and in specimens from other intrusions, notably from the upper part of the Mount Sedgwick laccolith and from the Tasman Island sill, lamellas of a clinopyroxene occur in the partings of the hypersthene. In sections parallel to (100) the lamellas appear as bright bands parallel to the cleavage, and in twinned crystals this also gives rise to a striking herringbone pattern (Fig. 14). In sections approaching (001) the included clinopyroxene appears as blebs and rods and sometimes shows a more or less graphic structure (Fig. 15). In some crystals the lamellas occur in two sets obliquely inclined to each other. These intergrowths closely resemble those described by H. H. Hess and A. H. Phillips.[49]

They offered two alternative explanations for the development of this structure: (1) that a clinopyroxene of the pigeonite type crystallized first and on slow cooling inverted to orthopyroxene with the segregation of diopsidic lamellas or (2) that an orthopyroxene separated which was capable of holding in solution diopsidic pyroxene to the extent of about 9 per cent, but unmixed on further cooling.

In the Tasmanian dolerites the structure appears at those levels in the sills at which plutonic pigeonite makes its first appearance. In

[48] "Some Data on the Iron-rich Hypersthenes," *Min. Mag.*, Vol. XXIV (1935), p. 221.

[49] "Orthopyroxenes of the Bushveld Type," *Amer. Min.*, Vol. XXIII (1938), pp. 450–56.

the Mount Sedgwick laccolith the lamellas of clinopyroxene first appear at the margins of the hypersthene crystals. Higher in the laccolith, however, they occur toward the interior of the hypersthene crystals and are enclosed by a margin of clear pyroxene. In a number of instances this marginal pyroxene, though physically continu-

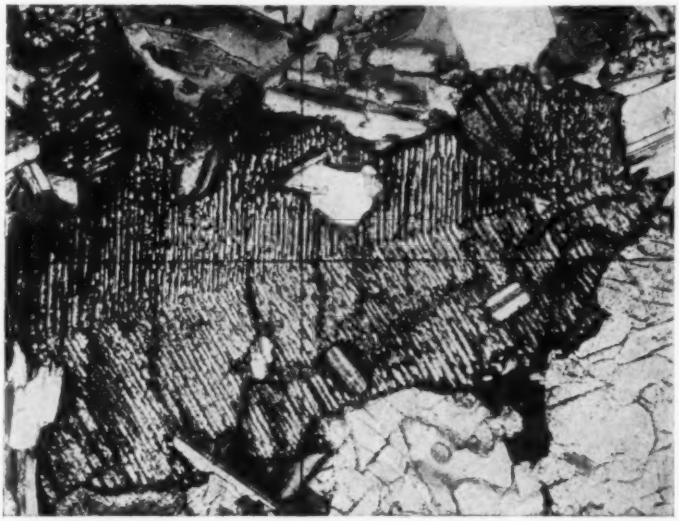

FIG. 14.—Photomicrograph of a twinned crystal of hypersthene, showing exsolution lamellas of clinopyroxene arranged in herringbone pattern in the cleavages. Mount Wellington sill, from 75 feet below the magnesia-rich layer. Mag. ×90. (Photo by J. S. Mann.)

ous with the remainder of the crystal, appears to be plutonic pigeonite rather than hypersthene. It appears, therefore, that the intergrowth marks an intermediate stage in the passage of hypersthene to plutonic pigeonite. At higher levels in the sills, where pigeonite has taken the place of orthopyroxene, the intergrowths are not found, although the pigeonites show a pronounced parting that in some respects resembles the lamellar intergrowth structure. Although three distinct varieties of plutonic pyroxene are found in the sills, two of them—the orthopyroxene and the plutonic pigeonites—are comple-

mentary in that the orthopyroxene ceased to form once the pigeonite appeared; and, if the above interpretation is correct, the orthopyroxenes and the plutonic pigeonites can be regarded as a single group of pyroxenes, which are immiscible with the augite series that crystallized out simultaneously with them. The pigeonites will be

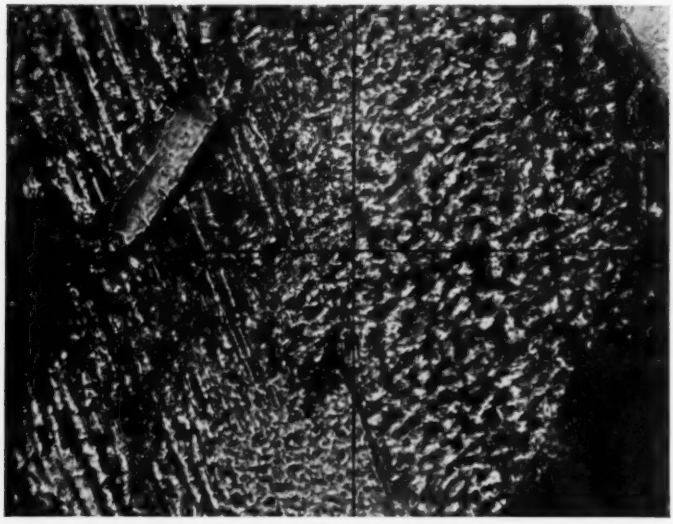

FIG. 15.—Photomicrograph of a graphic intergrowth of exsolution clinopyroxene in hypersthene. Same thin section as Fig. 14. Mag. ×150. (Photo by J. S. Mann.)

referred to, therefore, in the subsequent discussion of the pyroxenes as "plutonic pigeonites of the orthopyroxene sequence," to distinguish them from other plutonic pigeonites that bear a comparable relationship to augite.

4. MINOR CONSTITUENTS

ALKALI FELDSPARS

Alkali feldspar, intergrown with fine rods of plagioclase and quartz, occurs in intersertal patches in all but the most rapidly cooled phases of the dolerites; and the volume of these areas increases with progressive differentiation, until in the more acid layers and in the pegmatitic segregations it amounts to a feldspathic

mesostasis. The alkali feldspar is colorless or clouded, but untwinned, and has a lower refractive index than quartz, so that it is presumably orthoclase or anorthoclase. It frequently forms microintergrowths with the plagioclase rods, which are arranged in plumose sheaves or in lattice patterns.

QUARTZ

Quartz is always present in these patches of feldspathic mesostasis and generally occurs in micrographic intergrowth with the alkali feldspar. The proportion of such intergrowths increases with the volume of mesostatis. In the more acid differentiates and in the pegmatitic segregations the quartz occasionally occurs as small allotriomorphic grains; and in one section a row of these grains amounted almost to a veinlet.

It is probable that more detailed field work may reveal local concentration of the quartz and alkali feldspar as small veins of residual material such as occur in the Palisade sill.[50]

CHLORITE

Chlorite is present in variable, but small, amounts in many of the thin sections as an alteration product of the pyroxenes. Where these have well-developed partings, the chlorite appears as fibrous growths in the partings, giving the pyroxene a darkened or patchy appearance. Occasionally the chlorite forms a greenish, fibrous margin to crystals of pyroxene, in which situation it is studded with precipitated granules of iron ore. This indicates that the chlorite is a magnesia-rich variety. Occasionally, where the chlorite has completely replaced a pyroxene crystal, it occurs in larger, platy crystals.

The association of biotite and calcite with the chlorite indicates that it is of deuteric origin, but the amount of it present is rarely sufficient to warrant the use of the term "diabase" instead of "dolerite" for the rock.

BIOTITE

Small flakes of biotite, about 0.05 mm. long, occur occasionally near the margins of pyroxene crystals that have been partially altered to chlorite. They are pleochroic, with X = golden brown,

[50] Walker, *op. cit.*, p. 1065, and Analysis No. 20.

Y = greenish brown, Z = pale brown, and have a very small $(-ve)2V$. From its constant association with chlorite, and occasionally calcite, the biotite is probably of deuteric origin.

AMPHIBOLE

Amphibole is a rare mineral in the dolerites; but small, well-formed prisms of brown hornblende, pleochroic from dark brown to yellow-brown, form a marginal growth on crystals of augite in a section from the andesitic phase near the summit of Gunning's Sugarloaf. The hornblende is associated with chlorite.

The only other occurrence of amphibole noted is the presence of small prisms of an emerald-green amphibole, pleochroic to yellow-green, in the feldspathic mesostasis of the pegmatitic segregation found on Mount Sedgwick. It has a low extinction angle, and this, combined with its color, suggests that it is a soda amphibole.

CALCITE

Calcite is a rare mineral in the dolerites but occurs as small irregular areas associated with a large area of chlorite in a section from the Mount Wellington sill.

IRON ORE

Iron ores are practically absent from the chilled margins of the dolerites, but they become increasingly prominent in the more acid layers of the sills, where they form scattered crystals which may attain a diameter of 1.0 mm. The crystals tend to be idiomorphic but are sometimes intimately intergrown with pyroxene crystals. The maximum development of this coarse-grained iron ore is met in the pegmatitic segregations. Examinations of polished sections of the iron ore in reflected light reveals that the iron ore consists of a typical exsolution intergrowth of lamellas of ilmenite in the octahedral planes of magnetite. Some of the ilmenite lamellas are quite broad, but others can be detected only with high magnification. Diffusion and segregation of the ilmenite has led to a separation of irregular-shaped areas of ilmenite at the margins of some of the magnetite crystals, indicating a moderately slow rate of cooling.[51] The ilmenite may constitute as much as one-third of a crystal.

[51] W. H. Newhouse, "Opaque Oxides and Sulphides in Common Igneous Rocks," *Bull. Geol. Soc. Amer.*, Vol. XLVII (1936), p. 1; Edwards, "Some Ilmenite Microstructures and Their Interpretation," *Proc. Australian Inst. Min. Met.*, No. 110 (1938), pp. 48–52.

SULPHIDES

Pyrite is present in a number of specimens ranging from chilled margins to acid phases. The size of the crystals varies from minute grains scattered through the rock to areas 1.0 mm. across. Examination of polished sections show that this pyrite is generally present as clusters of minute idiomorphic crystals, sometimes molded about crystals of iron ore, sometimes forming strings of crystals in the grain boundaries or partings of the silicate minerals.

A few small grains of chalcopyrite were noted as inclusions in the magnetite-ilmenite grains.

APATITE

This is surprisingly rare in the dolerites and has been noted chiefly as needles in the mesostasis of the more acid differentiates and the pegmatitic segregations.

CRYSTALLIZATION OF THE PYROXENES[52]

The following discussion is based on the data available for the Mount Wellington sill; but, in view of the evidence given above and particularly Figure 13, it is assumed that it applies to the Tasmanian dolerites as a whole. The discussion turns largely on the optical measurements provided by Dr. Turner, and it is assumed that these are representative. Some error is involved here, because T. Krokstrom[53] has shown that the optical properties and composition of a particular mineral in a given rock specimen range about a mean value in the proportions of a Gauss frequency curve. This variation in composition arises from local variations in the rate of diffusion during crystallization; and the scatter of $2V$ values recorded by Dr. Turner in a single thin section indicates a similar variation in the pyroxenes under discussion. The error likely to arise

[52] Cf. the conclusions of H. H. Hess ("Pyroxenes of Common Mafic Magmas," *Amer. Min.*, Vol. XXVI [1941], pp. 515–35), which have appeared since this manuscript was posted to America. [*Editor's note:* Manuscript received September 9, 1941. Dr. Edwards thus reached his conclusions regarding pyroxene crystallization without knowledge that the work of Dr. Hess was appearing in the September and October (1941) numbers of the *American Mineralogist*. The reader will find an interesting case of parallel development of observational data and conclusions by independent workers. N. L. B.]

[53] "The Hallefors Dolerite Dyke and Some Problems of Basaltic Rocks," *Bull. Geol. Soc. Upsala*, Vol. XXVI (1936), pp. 154–59.

from this variation has been countered to some extent by averaging the several deduced compositions for the pyroxenes in any one thin section.

The average compositions of the various pyroxenes obtained in this way at different levels in the Mount Wellington sill (Tables 11, 12, and 13) are plotted in a triangular diagram in Figure 16, which provides a graphic summary of how the pyroxenes have crystallized

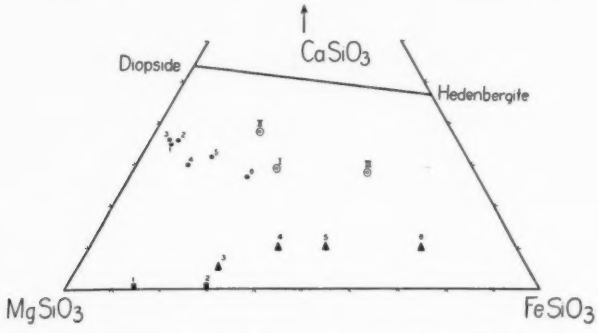

FIG. 16.—Crystallization trends of pyroxenes in the Mount Wellington sill. ● = augites; ■ = orthopyroxenes; ▲ = pigeonites; ○○ = analyzed composite pyroxenes. The numbers 1–6 indicate the sequence of crystallization and the position in the sill, as recorded in Tables 11, 12, and 13. Pyroxenes with the same number crystallized simultaneously. Of the analyzed composite pyroxenes, I = pyroxene from the chilled contact of the sill (the "mean pyroxene of the sill"); II = pyroxene from Cataract Gorge, Launceston; III = pyroxene from the summit of Mount Wellington, as shown in Table 10. The lime content of these composite pyroxenes is probably high, owing to incomplete separation from plagioclase prior to analysis.

as differentiation progressed. The three analyses of the composite pyroxenes given in Table 10 have been reduced to a similar basis by calculating their CaO, MgO, and FeO contents as $CaSiO_3$, $MgSiO_3$, and $FeSiO_3$ and plotting the ratio obtained after converting to 100 per cent; they confirm the general trends shown by the optical data, especially if allowance is made for the possibility that their CaO contents are high through slight contamination of the analyzed powders with unseparated plagioclase. Four facts emerge from the diagram: (1) sudden chilling of the dolerite magma caused the precipitation of a metastable pigeonite, whose composition corresponds closely to the

"mean composition" of all the varieties of pyroxene formed in the dolerites according to their relative abundance; (2) at every stage in the differentiation of the sill, two immiscible series of pyroxenes crystallized simultaneously; (3) as differentiation proceeded, each series of pyroxene became enriched in $FeSiO_3$ relative to its other constituents; (4) the rate and extent of enrichment in $FeSiO_3$ was much faster and more complete in the orthopyroxenes and the plutonic pigeonites than in the augites.

Crystallization of the pyroxenes began with the formation of bronzite, and for a short time this was the sole pyroxene forming. At an early stage in the cooling of the intrusion the orthopyroxene was joined by a magnesia-rich augite, and these two pyroxenes continued to crystallize side by side, the later-formed members of the orthopyroxene series becoming enriched in $FeSiO_3$ relative to the earlier ones, while the augite maintained a constant composition. These facts are in keeping with the observations of R. B. Sosman[54] and B. Asklund[55] that there is an immiscibility gap between the augites, on the one hand, and the orthopyroxenes and magnesia-rich clinopyroxenes, on the other, and those of S. Tsuboi[56] as to the behavior of the phenocrystic pyroxenes in the two-pyroxene andesites of Japan. The orthopyroxene of the Tasmanian dolerites is restricted to the chilled margins of the intrusions and to the lower third of the sills. At a later stage in the differentiation of the intrusions it gave place to a plutonic pigeonite, such as H. Kuno[57] has recorded in certain Japanese extrusive rocks. In the upper parts of the sill, augite continued to crystallize side by side with this pigeonite, and during this stage the augite as well as the pigeonite became richer in iron as differentiation progressed, although the enrichment of the augite in iron progressed less rapidly than the enrichment of the pigeonite in

[54] "Minerals and Rocks of the Composition $MgSiO_3$-$CaSiO_3$-$FeSiO_3$," *Jour. Wash. Acad. Sci.*, Vol. I (1911), pp. 54–56.

[55] "Petrological Studies in the Neighbourhood of Stavsjo, in Kolmarden," *Arsbok. Sver. Geol. Undersok.*, Vol. XVII, No. 6 (1923).

[56] "On the Course of Crystallization of Pyroxenes from Rock-Magmas," *Jap. Jour. Geol. & Geog.*, Vol. X (1932), p. 67.

[57] "On the Crystallization of the Pyroxenes from Rock-Magmas, with Special Reference to the Formation of Pigeonite," *Jap. Jour. Geol. & Geog.*, Vol. XIII (1936), p. 141.

iron, as may be seen from Figure 16. This continued formation of two immiscible pyroxenes is at variance with Kuno's suggestion that, once the iron content of the pyroxene material has exceeded a certain value, about 48 per cent $FeSiO_3$, a single plutonic pigeonite should take the place of the two immiscible pyroxenes. It finds some parallel, however, in the behavior of the pyroxenes in the Palisade sill of New Jersey,[58] in the Downes Mountain sill of the Karro series,[59] and in the dolerite sills of Antarctica,[60] where plutonic pigeonite and iron-rich augite (hypersthene-augite) crystallized simultaneously. So constant a behavior indicates that it is a characteristic feature of the pyroxenes of moderately slowly cooled tholeiitic magmas and that it is the normal continuation under such conditions of the immiscibility of augite and orthopyroxene under conditions of slow cooling.

Wager and Deer[61] have accepted Kuno's picture of a "two-pyroxene field" of crystallization and a "pigeonite field" of crystallization in a modified form, in which the area of the pigeonite field is more restricted than as suggested by Kuno. In the Skaergaard intrusion they have traced a pyroxene sequence which begins as augite and passes to a pigeonite of composition $CaSiO_3$ = 30.0, $MgSiO_3$ = 1.5, $FeSiO_3$ = 68.5. This sequence corresponds in a sense to the augite sequence in the Mount Wellington sill, which is richer in $MgSiO_3$ at the outset and never gets beyond a composition of $CaSiO_3$ = 27, $MgSiO_3$ = 48, $FeSiO_3$ = 25.

As the argument that follows will show, there is some reason to believe that if the Mount Wellington sill had been thicker, so that differentiation could have progressed to greater extremes, then the final product of the augite sequence would have had a composition approaching that of the middle members of the Skaergaard augite sequence. The plutonic pigeonite sequence in the Mount Wellington sill, on the other hand, although it begins as a magnesia-rich member, ends as an iron-rich member of a composition about $CaSiO_3$ =

[58] Walker, *op. cit.*

[59] F. Walker and A. Poldervaart, "The Petrology of the Dolerite Sill of Downes Mountain, Calvinia," *Trans. Geol. Soc. South Africa*, Vol. XLIII (1941), p. 163.

[60] Browne, *op. cit.*, p. 246.

[61] "The Petrology . . . . ," *op. cit.*, pp. 258–60, Fig. 56.

10, $MgSiO_3$ = 20, $FeSiO_3$ = 70, which lies within the so-called "pigeonite field" either as drawn by Kuno or as modified by Wager and Deer. The combined data of the Skaergaard intrusion and the Mount Wellington sill show, then, that both the augite sequence of pyroxenes and the orthopyroxene or its plutonic pigeonite sequence of pyroxenes can produce end members which lie within the so-called "pigeonite field" but are of different composition; and the fact that, in the Mount Wellington sill, members of the augite sequence were still crystallizing when the pigeonite sequence had entered the pigeonite field suggests that the hypothetical two-pyroxene boundary does not exist. Instead, as the considerations that follow will indicate, it is probable that under conditions of cooling, comparable with those occurring in dolerite sills 1,000 feet or more thick, the immiscibility that is found to exist between augites, on the one hand, and clinoenstatites or enstatites, on the other, continues to exist between them as they become enriched in iron, so that in tholeiitic magmas at every stage of differentiation two immiscible pyroxenes—one a member of the augite sequence and the other a member of the orthopyroxene or its plutonic pigeonite sequence—will crystallize simultaneously.

Relation to Atomic Structure

The behavior of the pyroxenes in general and those of the Mount Wellington sill in particular can be explained by reference to the atomic structure of the pyroxenes as established by X-ray investigations. Diopside consists of parallel chains of silicon and oxygen atoms bound together by the calcium and magnesium atoms, each of which is surrounded by six "active" oxygen atoms.[62] Each active oxygen atom is linked to one calcium atom and one magnesium atom. This structure appears to be characteristic of all the monoclinic pyroxenes like augite, hedenbergite, and clinoenstatite. Enstatite has a similar structure, but a slight variation in the arrangement of the silicon-oxygen chains gives it a higher symmetry.

The ionic radii of the three chief cations concerned in the pyroxene structures are Ca^{++} = 1.06, Mg^{++} = 0.78, and Fe^{++} = 0.83. It fol-

[62] W. L. Bragg, "Atomic Structure of Minerals," *George Fisher Baker Lectures* (Ithaca, N.Y.: Cornell University Press, 1937), pp. 187–90.

lows that Fe^{++} can replace Mg^{++} without causing undue distortion of the pyroxene structures. On the other hand, introduction of the small Mg^{++} or Fe^{++} ions in place of the large Ca^{++} ion will cause considerable distortion of the structure; and it seems likely that, if the structure is to remain stable, such replacement would be possible only to a limited extent.

Extensive isomorphous replacement can be expected between $MgSiO_3$ and $FeSiO_3$; and, as the proportion of $FeSiO_3$ increases, the dimensions of the links between the silicon-oxygen chains will be increased somewhat, so that a small, but increasing, proportion of large Ca^{++} ions will tend to enter the pyroxene structure. Study of the system MgO-FeO-SiO_2[63] shows that the clinoenstatites are high-temperature minerals, which invert at lower temperatures to enstatites, and that the inversion temperature decreases as the iron content of the clinoenstatite rises. At first, therefore, the magnesia-rich pyroxenes might crystallize at temperatures below the inversion temperature, and so crystallize as orthopyroxenes; but with increase of iron content they might crystallize above the inversion temperature and form clinopyroxenes, namely, the plutonic pigeonites. When the first such pigeonite formed, the balance between temperature of crystallization and temperature of inversion would be delicate, and the first-formed pigeonite might easily invert to orthopyroxene, causing any $CaSiO_3$ in solid solution to unmix as augite. This would explain the occurrence of exsolution intergrowths of augite in hypersthene at about those levels in the sills where hypersthene began to give place to stable pigeonites; and it would explain why the exsolution lamellas first appeared at the margin of the hypersthene crystals and later appeared at the centers of the hypersthene crystals, surrounded by a clear margin of pigeonite optically and physically continuous with the hypersthene. Later-forming pigeonite would crystallize at temperatures above the inversion temperature and would remain increasingly stable in sill-like intrusions with a moderate rate of cooling. In more slowly cooled intrusions they might crystallize throughout as orthopyroxene or else crystallize as pigeonite and subsequently invert to orthopyroxene, as

[63] N. L. Bowen and J. F. Schairer, "The System MgO-FeO-SiO_2," *Amer. Jour. Sci.*, Vol. XXIX, pp. 200–203.

has happened, perhaps, in the Skaergaard intrusive.[64] Complete isomorphism between augite and clinoenstatite or between hedenbergite and clinoferrosilite should be impossible under conditions permitting stable development; and $MgSiO_3$ or $FeSiO_3$ in excess of the limit, being unable to enter the augite structure, would crystallize as clinoenstatite or enstatite or their iron-rich equivalents. There should also be an upper limit to the amount of $CaSiO_3$ that could be present in the magnesium-iron pyroxenes, if the pyroxene structure is to remain stable. Under the conditions of rapid crystallization that attend extrusion or marginal chilling of a basaltic magma, the excess $MgSiO_3$ and $FeSiO_3$ do enter the augite structure. Work with artificial melts has shown that under such conditions a complete series of solid solutions can exist between augite and clinoenstatite.[65] Such pyroxenes should, however, be unstable; and X-ray investigations suggest that this is so and that if such pyroxenes were cooled slowly the clinoenstatite component would invert to enstatite, while the diopside component would unmix.[66] Where such pyroxenes (pigeonites) occur "as part of the general fabric of basaltic rocks, they were probably formed metastably during rapid crystallization."[67]

The fact that Fe^{++} can replace Mg^{++} more readily than Ca^{++} should also control the way in which augites become enriched in iron. In the early stages of such enrichment, Fe^{++} would be able to replace both Mg^{++} and Ca^{++}. Replacement of Ca^{++} by Fe^{++} could continue with increasing distortion of the pyroxene structure, until the Ca^{++} content of the structure was reduced to a limit beyond which further replacement of it by Fe^{++} would render the structure unstable. Further enrichment of the augite in iron could develop only by replacement of Mg^{++}. This explains the behavior of the augite sequence of pyroxenes in the Skaergaard intrusion. As Wager and Deer[68] have shown, the earliest augite to crystallize is a lime-rich

[64] Wager and Deer, "The Petrology . . . . ," *op. cit.*, pp. 82–83.

[65] Bowen, "The System Forsterite-Diopside-Silica," *Amer. Jour. Sci.*, Vol. XXXVIII (1914).

[66] R. W. G. Wyckoff, H. E. Merwin, and H. S. Washington, "X-ray Diffraction Measurements upon the Pyroxenes," *Amer. Jour. Sci.*, Vol. X (5th ser., 1925), p. 395.

[67] Bowen and Schairer, *op. cit.*

[68] "The Petrology . . . . ," *op. cit.*, p. 241, Fig. 48.

variety. During the early stages of enrichment in iron the $CaSiO_3$ content decreases from 47 to 32 per cent, while the $MgSiO_3$ content decreases only from 34 to 32 per cent (Fig. 17). From that stage onward, however, the $CaSiO_3$ content decreases only slightly to 27 per cent, and the increase in $FeSiO_3$ is chiefly at the expense of the $MgSiO_3$. In the closing stages of the sequence the lime content of the residual magma has been built up so that $CaSiO_3$ tends to take the place of $FeSiO_3$ again. If the explanation of this behavior is as sug-

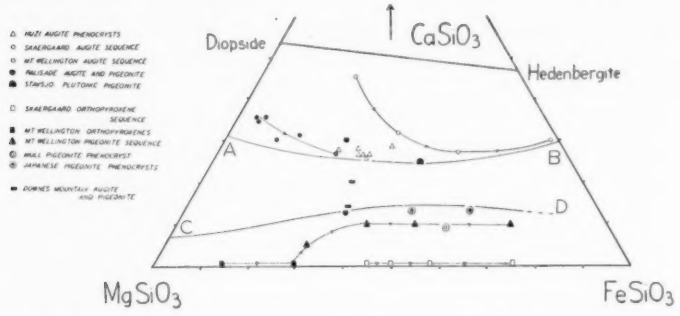

FIG. 17.—Diagram to show the courses of crystallization of pyroxenes, as inferred in the present discussion. The width of the immiscibility gap *ABDC* may vary from zero for rapidly cooled magmas to the widths shown for moderately slowly cooled magmas. In still more slowly cooled magmas the line *CD* may coincide with the composition line $MgSiO_3$–$FeSiO_3$.

gested above, then the $CaSiO_3$ content of the Skaergaard augites, during the period when iron is replacing chiefly magnesium, should represent about the lower limit to which the $CaSiO_3$ content of augite can be reduced if the structure of the pyroxene is to remain stable. Turning to the Mount Wellington augite sequence, Figure 17 shows that here, again, iron was able to replace both calcium and magnesium during the early stages of enrichment of the augite in iron and that the $CaSiO_3$ content of the most iron-rich augite is practically the same as that of the later Skaergaard augites. In the Palisade sill[69] the hypersthene-augite again has $CaSiO_3$ = 30, prior to further enrichment in iron. None of the intratelluric augites plotted by Kuno[70] contains less than this amount of $CaSiO_3$. In the rocks of

[69] Walker, *op. cit.*, p. 1071.

[70] *Op. cit.*, p. 147, Fig. 4.

the Huzi Volcanic Zone of Japan,[71] one augite is recorded of the composition $CaSiO_3 = 26$, $MgSiO_3 = 42$, $FeSiO_3 = 32$, and a number of others in which $CaSiO_3$ ranges from 27 to 32 per cent. These all occur in association with phenocrysts of hypersthene. A pigeonite in a gabbro at Stavsjo, Sweden,[72] has a $CaSiO_3$ content of 25 per cent. It is suggested, therefore, that under conditions of moderately slow cooling the limit of stability of the atomic structure of augites, or of pigeonites belonging to an augite sequence,[73] is reached when the $CaSiO_3$ content of the pyroxene falls to 25–30 per cent. The line *AB* in Figure 17 marks approximately the augite boundary of the pyroxene immiscibility gap for such conditions.

The upper limit of the amount of $CaSiO_3$ that can enter into the atomic structures of the orthopyroxenes and the pigeonites belonging to an orthopyroxene sequence can be established approximately in the same way. In the pyroxenes of this type in the Mount Wellington sill, the $CaSiO_3$ content rises to about 10 per cent and then remains constant. In the data quoted by Kuno[74] the maximum $CaSiO_3$ content of pyroxenes of this type reaches 13 per cent, and the same $CaSiO_3$ content is found in the pigeonites of the Palisade sill.[75] The $CaSiO_3$ content of orthopyroxenes of the Bushveld type is about 5 per cent.[76] These values appear, then, to mark the upper limit to which the $CaSiO_3$ content of orthopyroxenes and related pigeonites can rise under conditions of moderately slow cooling; and the line *CD* has been drawn accordingly to mark the approximate position of the orthopyroxene boundary of the pyroxene immiscibility gap for such conditions. Only metastable pigeonites can lie within this immiscibility gap *ABDC* (and they may overlap it); above and below it lie, respectively, the field of the augites and their related plutonic pigeonites and the field of the orthopyroxenes and their related plutonic pigeonites.

[71] H. Tsuya, "On the Volcanism of the Huzi Volcanic Zone with Special Reference to the Geology and Petrology of Idu and the Southern Islands," *Bull. Earthquake Res. Inst. Tokyo*, Vol. XV, Part 1, pp. 216–350, Fig. 14.

[72] Asklund, *op. cit.*, p. 26.

[73] Ferro-augites of Hess (*op. cit.*, pp. 517–18).

[74] *Op. cit.*, p. 146, Fig. 4.

[75] Walker, *op. cit.*, p. 1072.

[76] Hess and Phillips, *op. cit.*, p. 454.

One discrepancy has been found, however, that may invalidate this picture or at least call for its modification. In the Downes Mountain sill,[77] the $CaSiO_3$ content of the pigeonite in the orthopyroxene sequence is given as 14 per cent, which is reasonably close to the orthopyroxene boundary; but the $CaSiO_3$ content of the hypersthene-augite is given as 20 per cent, so that it lies well within the field of metastable pigeonite, as drawn in Figure 17, and yet behaves as a member of an augite sequence. This may indicate, as Walker and Poldervaart appear to think, that pigeonites of the augite sequence and pigeonites of the orthopyroxene sequence merge into one another when enriched in iron beyond this point. It seems probable, however, that the width of the immiscibility gap between the augite series and the clinoenstatite series ranges from zero to a maximum according to the temperature and particularly the rate at which crystallization takes place. At high temperatures and with rapid cooling, complete miscibility is found; at lower temperatures and with slow cooling a maximum immiscibility results. At intermediate temperatures and with intermediate rates of cooling a degree of immiscibility intermediate between these two extremes might be expected; and the pyroxenes of the Downes Mountain sill appear to be a case in point, since the Downes Mountain sill, being only 200 feet thick, must have cooled rather more rapidly than sills 1,000 feet or more thick.

In very slowly cooled magmas in which the temperature of crystallization remains below the inversion temperature the orthopyroxenes will not give place to pigeonites, and the line *CD* of Figure 17 will tend to coincide with the composition line $MgSiO_3$-$FeSiO_3$, giving the maximum immiscibility. The proportions of the two series of pyroxenes forming at any stage of differentiation will depend on the composition of the residual magma at that stage; and the relative proportions of MgO, CaO, and Al_2O_3 in the magma will determine whether such plutonic pigeonite of the orthopyroxene sequence as may form will contain the maximum or less than the maximum amount of $CaSiO_3$ permitted by its temperature and rate of crystallization.

[77] Walker and Poldervaart, *op. cit.*, pp. 163–64.

THE DIFFERENTIATION PROCESS

Three factors have dominated the differentiation of the dolerite magma: (1) fractional crystallization, (2) gravitational differentiation, and (3) the form of the intrusion concerned. The sinking of early-formed pyroxenes rich in magnesium gave rise to a progressive increase in the proportion of FeO:MgO in the later-formed pyroxenes—a feature which is characteristic of the dolerites as a whole. There is an important difference, however, between the trend of differentiation within the sills and the trend of differentiation in the dikelike intrusions, as may be seen by a comparison of Figures 8, 9, and 12. In the sills there has been absolute enrichment of the late-residual magma in iron, accompanied by impoverishment in soda and alumina. In the dikelike masses, on the other hand, the late-residual magma became slightly impoverished in iron but showed a steady enrichment in soda and alumina. The difference arises from the different forms of the intrusive bodies. The sills are *closed chambers*, in which early-formed pyroxene and plagioclase sank at different rates and accumulated above the chilled bases, displacing the residual liquid into the upper parts of the sills. Selective removal of the magnesium in the early-formed pyroxene concentrated the iron in these shrinking volumes of liquid. When the iron crystallized, the iron-rich minerals that formed could not sink past the already accumulated, early-formed minerals, and so a layer of iron-enriched rock occurs in the upper parts of the sills. The dikelike bodies, on the other hand, may be described as *subjacent chambers*, the term "subjacent" being used in the sense defined by Daly,[78] namely, that the bodies so designated have no visible floor and extend downward to some unknown limit. In these subjacent bodies the early-formed crystals did not accumulate but, as far as the visible portion of the dikelike bodies is concerned, sank out of the chamber. The residual liquid in the visible portions of the chamber was displaced upward as in the sills, and in addition a volume of fresh undifferentiated magma equal to the volume of the sinking crystals was displaced upward from the depths into the visible portion of the

[78] *Igneous Rocks and the Depths of the Earth* (New York: McGraw Hill Book Co., 1933), p. 75.

chamber. Fractional crystallization, as before, caused a concentration of iron in the upper parts of the chamber. When this iron commenced to crystallize, the iron-rich pyroxenes that formed were able to sink freely because of the absence of a floor of accumulated crystals beneath them. The higher specific gravity of the iron-pyroxenes enabled them to sink more rapidly than the plagioclase crystallizing at the same time, and so the residual melt tended to become enriched in the feldspar constituents. The continued displacement upward of undifferentiated magma throughout the process maintained the most differentiated magma near the tops of the dikelike bodies. Convection currents may have modified this simple picture, but they do not appear to have interfered with the general trend.

In both forms of intrusion a concentration of iron must have developed in the upper part of the chamber; but, whereas in the sills this concentration was maintained, in the dikelike bodies it was dissipated. Presumably, iron-rich layers might be expected in the deeper parts of the dikelike bodies as layers of accumulation or remelts of accumulated iron-rich pyroxenes; but rocks so derived would differ in composition from the iron-rich rocks formed in the sills.

If differentiation had continued to further extremes, the iron-rich layers in the sills would have given place upward, fairly rapidly, to an acid feldspathic residuum, which upon the exhaustion of the plagioclase would have approached the composition of a granophyre. In the dikelike bodies the observed transition from tholeiitic basalt in the chilled margins to an andesitic phase in the central portions would have continued and would have given rise to an end-product similar to that postulated for the sills.

In the dikelike bodies there would also have developed a similar gradation downward from the acid rocks below the chilled tops to little-differentiated rock; but the transition to more basic types would have continued below this layer of little-differentiated rocks to layers increasingly enriched in iron and, at still greater depths, to rocks enriched in magnesium rather than iron. The Glen More Ring-dike of Mull[79] appears to be a striking instance on a small scale of

[79] E. B. Bailey, H. H. Thomas, and C. T. Clough, "The Tertiary and Post Tertiary Geology of Mull," *Mem. Geol. Surv. Scotland, 1924*, pp. 320–30; C. Koomans and P. H. Kuenen, "On the Differentiation of the Glen More Ring-Dyke, Mull," *Geol. Mag.*, Vol. LXXV (1938), p. 145.

differentiation in a subjacent chamber. Here, in the lowest portion of the chamber that is visible, an iron-enriched layer is found that grades up into rock of the original basaltic (tholeiite) composition, which, in turn, grades up into granophyre.

An example on a larger scale is provided by the Yogo Peak stock, in the Little Belt Mountains of Montana,[80] where there is transition from shonkinite at the margins of the stock through monzonite and from syenite-porphyry to granite porphyry in the core of the stock.

This conception of closed and subjacent chambers, in which identical processes of fractional crystallization and gravitational separation can give rise to different trends of differentiation, seems of fundamental importance in petrogenesis and explains a number of otherwise irreconcilable observations. C. N. Fenner[81] has long maintained that fractional crystallization of basaltic magma must lead to an enrichment of the residual magma in iron.

Wager and Deer's[82] study of the Skaergaard intrusive has provided a striking example of this trend, though the final product of differentiation bears considerable resemblance in composition to the dacitic glass which, Walker[83] found, forms the base of the tholeiite of Kinkell, Scotland.

This trend toward the enrichment of the residual magma in iron relative to magnesia is strongly marked in the Tasmanian dolerites and, as Wager and Deer indicate, is so characteristic of basalts in general that it may be regarded as the normal trend in the differentiation of basaltic magma. Wager and Deer go further, however, and conclude that iron-rich rocks of ferro-gabbro composition, such as they found in the Skaergaard intrusive, are the invariable product of this trend; and, because such rocks are extremely rare, they argue

[80] W. H. Weed and L. V. Pirsson, "Igneous Rocks of Yogo Peak," *Amer. Jour. Sci.*, Vol. L (3d ser., 1895), p. 467; "Geology of the Little Belt Mountains, Montana," *20th Ann. Rept. U.S. Geol. Surv., 1900*, Part III, pp. 318, 563–68.

[81] "The Crystallization of Basalts," *Amer. Jour. Sci.*, Vol. XVIII (1929), p. 225; "The Residual Liquids of Crystallizing Magmas," *Min. Mag.*, Vol. XXII (1931), pp. 539–60; "Olivine Fourchites from Raymond Fosdick Mountains, Antarctica," *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938), p. 367.

[82] "The Petrology . . . . ," *op. cit.*

[83] F. Walker, "The Late-Palaeozoic Quartz-Dolerites and Tholeiites of Scotland," *Min. Mag.*, Vol. XXIV (1938), p. 131.

that it is most unlikely that basaltic magma could give rise to rocks of the calc-alkaline series.

The Skaergaard intrusive owes its unusual features to the fact that it underwent strong fractional crystallization in a closed chamber, on a larger and more impressive scale than anything hitherto recorded. A parallel trend of differentiation is found, however, in lesser intrusive bodies, like the Mount Wellington sill and the Palisade sill,[84] which also underwent fractional crystallization in closed chambers. In each, differentiation is accompanied by an absolute increase in iron content in the upper part of the intrusion with less pronounced increases in soda, potash, and titania. Each shows a marked decrease in MgO in the upper levels. In all three the alumina content, which in the lower portions is less than that of the undifferentiated magma, first increases and then decreases at increasingly higher levels in the intrusion. The scale of the changes is smaller in the lesser bodies and is somewhat affected by the fact that the original magma in the two sills considered was a saturated basalt or tholeiite, while that at Skaergaard was an undersaturated olivine basalt. The same trend toward absolute enrichment in iron in the upper levels is also shown in a small differentiated sill near Electric Peak, Yellowstone Park.[85]

To suggest that the trend of differentiation in the Skaergaard intrusive or in these sills is the only normal way in which such basaltic magmas could differentiate is, however, to ignore the fact that in each case the differentiation took place in a closed chamber. When such magmas differentiate by identical processes in subjacent chambers, they follow quite different trends.

If the differentiation of a basaltic magma proceeds in a subjacent chamber of batholithic proportions, then the later-formed ferromagnesian minerals will be enriched in iron relative to magnesium, as is noted in most rock series.[86] This will lead to temporary enrich-

[84] Walker, *op. cit.;* Fenner, "The Crystallization . . . . ," *op. cit.*, pp. 230–31.

[85] J. P. Iddings, "Differentiated Sheet South-east of Electric Peak," *U.S. Geol. Surv. Mono. 32*, Part 2 (1899), p. 82; Fenner, "The Crystallization . . . . ," *op. cit.*, pp. 228–29.

[86] N. L. Bowen, J. F. Schairer, and H. V. Willems, "The Ternary System Na_2SiO_3-Fe_2O_3-SiO_2," *Amer. Jour. Sci.*, Vol. XX (5th ser., 1935), p. 453.

ment of the residual magma in iron; but, once the iron crystallizes as ferromagnesian minerals, it will largely sink into the depths and tend to catch up with or outdistance more slowly sinking plagioclase of earlier generation, unless it is trapped by the onset of crystallization. The residuum at the top of such a chamber will tend to become more and more feldspathic and ultimately siliceous. Moreover, it will be buoyed up and reinforced by heavier undifferentiated magma displaced from the depths, so that it will tend to accumulate at the highest points of the chamber roof. Cupolas will develop above some of these points, and the acid-alkaline differentiates will concentrate in these protrusions above the main chamber and there undergo further differentiation. This view has been advanced to explain the recurring association of small volumes of related alkaline differentiates about localized centers of eruption in central Victoria[87] and in the Kerguelen Archipelago.[88] Where such a variety of differentiated rocks occur, associated with and intercalated with normal olivine-basalts, all having issued from the same volcanic hill[89] or from adjacent volcanic hills,[90] it is difficult to believe that they are not genetically related to the olivine basalt, particularly when similar associations are of world-wide occurrence.

The weight of evidence in this direction is so great that W. Q. Kennedy's[91] contention that trachytic and phonolitic rocks are the normal end-products of the differentiation of olivine-basalt (undersaturated) magma can be regarded as established.

There is a considerable probability that tholeiite (saturated) magma may give rise to acid or feldspathic differentiates in a comparable

[87] Edwards, "Three Olivine-Basalt-Trachyte Provinces and Some Theories of Petrogenesis," *Proc. Roy. Soc. Victoria*, Vol. XLVIII, Part 1 (new ser., 1936), p. 19.

[88] Edwards, "Tertiary Lavas from the Kerguelen Archipelago," *Reports Ser. A, British Australian New Zealand Antarct. Research Exped., 1929–1931*, Vol. II, *Geology*, Part 5 (1938), pp. 94–96.

[89] A. B. Edwards and W. Crawford, "The Cainozoic Volcanic Rocks of the Gisborne District, Victoria," *Proc. Roy. Soc. Victoria*, Vol. LII, Part 2 (new ser., 1939), pp. 281–311.

[90] E. W. Skeats and H. S. Summers, "The Geology and Petrology of the Macedon District," *Bull. Geol. Surv. Victoria*, Vol. XXIV (1912).

[91] "Trends of Differentiation in Basaltic Magmas," *Amer. Jour. Sci.*, Vol. XXV (5th ser., 1933), p. 293.

fashion; and it is of interest to note the considerable similarity between the most acid differentiate in the dikelike mass of Gunning's Sugarloaf and many of the two-pyroxene andesites of Japan (Table 14, Nos. 1, *A*, *B*). A perfect chemical match has not been found, but

TABLE 14

	1	*A*	*B*	2	*C*	*D*	3	*E*	*F*
SiO_2	54.74	54.00	54.70	56.74	56.62	56.70	47.92	49.28	49.21
Al_2O_3	19.56	18.84	20.18	15.46	15.49	15.90	18.87	19.53	18.51
Fe_2O_3	0.27	2.07	2.40	3.08	4.58	2.94	1.18	2.60	3.12
FeO	8.13	7.71	5.10	7.58	7.09	7.74	8.65	7.81	7.97
MgO	2.34	2.72	2.67	2.54	3.00	3.34	7.82	6.47	5.74
CaO	10.98	9.74	8.33	7.64	7.33	7.77	10.46	11.38	11.46
Na_2O	2.15	2.95	3.65	3.08	2.95	3.13	2.44	1.76	2.13
K_2O	1.47	0.41	0.77	1.59	0.55	0.74	0.19	0.16	0.47
H_2O+	0.23	0.30	0.75	1.28	0.35	0.36	0.41	.....	.....
H_2O-	0.21	0.20	0.40	.....	0.72	0.09	0.10	.....	.....
CO_2	nil	.....	.....	.....	.....	.....	0.06	.....	.....
TiO_2	0.66	1.02	0.93	1.26	0.96	1.24	1.42	0.76	1.04
P_2O_5	0.05	0.11	0.20	0.15	0.08	0.16	0.10	0.10	0.12
MnO	0.15	0.29	0.10	tr.	0.22	0.18	0.07	0.15	0.23
Total	100.04	100.36	100.22	100.40	99.94	100.29	99.63	100.00	100.00

1. Dolerite from the summit of Gunning's Sugarloaf, Tasmania.

A. Two-pyroxene andesite, lowest lava of the middle stage of the Taga volcano, Idu, Japan (H. Tsuya, *Bull. Earthquake Res. Inst.*, Vol. XV, Part I [1937], p. 273 [No. 65]).

B. Hypersthene-andesite, from Asitaka-yama volcano, Japan (*ibid.*, p. 277 [No. 68]).

2. Dolerite from North-West Bay, Tasmania.

C. Aphyric andesite, one of the middle lavas of the somma of Halcone volcano, Japan (*ibid.*, p. 262 [No. 421]).

D. Aphyric andesite, lava south of Aziro-mati, North Idu, Japan (*ibid.*, p. 247 [No. 32]).

3. Average chilled marginal gabbro, Skaergaard intrusive (L. R. Wager and W. A. Deer, *Meddeleser om Grønland*, Vol. CV, Part 4 [1939], Table 41).

E. Average Tertiary porphyritic basalt from Idu and Bonin, Japan (Tsuya, *op. cit.*, p. 341).

F. Average Quarternary porphyritic basalt from Idu and the Southern Islands, Japan (*ibid.*).

a closer match can be found for the differentiated rock from North-West Bay, which probably represents a slightly more advanced stage in the differentiation of a dikelike mass than that from Gunning's Sugarloaf (Table 14, Nos. 2, *C*, *D*). In the Japanese andesites that are most comparable, the MgO:CaO ratio is consistently higher than for the Gunning's Sugarloaf rock, and the K_2O content is lower, no doubt as a result of a difference in the composition of the primary

magmas concerned. If one imagines the differentiation of Gunning's Sugarloaf proceeding further on a larger scale, it is difficult to avoid the conclusion that the rocks that would have resulted would have been closely akin to andesites and other members of the calc-alkaline family. It is interesting to notice, in this connection, that the chilled margin of the Skaergaard intrusive, which represents the composition of the undifferentiated magma, bears a considerable resemblance to certain Tertiary basalts from Idu and the Southern Islands, in the Huzi Volcanic Zone of Japan (Table 14, Nos. 3, *E*, *F*). Again the resemblance is not exact, but it is sufficiently close for the different trend in differentiation of the two magmas to be significant.

It must be conceded, in view of these considerations, that calc-alkaline rocks can be derived from tholeiitic basalt magma and that the trend of differentiation shown by the Skaergaard intrusion does not, therefore, dispose of this possibility, because the Skaergaard intrusion provides a very special instance of differentiation in a closed chamber. This is not to claim that all calc-alkaline rocks are derived from basaltic magma but merely that some are. If the small volume of trachytic differentiates derived from olivine-basalt magma or of andesitic differentiates derived from Tasmanian dolerite is any guide, then the volume of calc-alkaline rocks derived directly from tholeiite magma should be equally small. The great volume of the calc-alkaline rocks is the chief reason for thinking that the bulk of them are not derived simply from the differentiation of tholeiitic magma.

In the author's opinion, which is based on studies of calc-alkaline rocks in Victoria,[92] the great bulk of them can have arisen, as Wager and Deer[93] suggest, only by the assimilation by tholeiitic magma of large quantities of sialic material coupled with crystallization differentiation in subjacent chambers.

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[92] "Quartz-Diorite Magma in Eastern Victoria," *Proc. Roy. Soc. Victoria*, Vol. L, Part 1 (new ser., 1937), pp. 97–108.

[93] "The Petrology . . . . ," *op. cit.*, p. 323.

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ANORTHOSITE AND ASSOCIATED ROCKS ABOUT NAIN, LABRADOR

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Cornell University

ABSTRACT

Salient compositional, textural, and structural features of the anorthosite and associated rocks about Nain, Labrador, are described. The rocks include an anorthositic gabbrodiorite group, with possibly younger diorite; an adamellite group, with tonalite and monzonite; the dike rocks associated with these major bodies, including pegmatites; older gneisses whose nature is uncertain; other highly metamorphosed gneisses in which the presence of garnet, cordierite, or graphite indicate a sedimentary component; and a less metamorphosed group of sediments. The features of an ultrabasic group occurring in small amounts throughout the region are discussed, with the suggestion that they may be skarn rocks. The age relations of these rocks are considered, with the conclusion that the anorthositic rocks are younger than the possibly Sudburian sediments. Some of the major structural relations of the region are outlined, with the conclusion that the banding and granulation of the igneous rocks are primary and that the anorthositic mass is, at least in part, floored. Features indicating the proximity of a roof and the existence of roof pendants in other parts of the area are discussed. Evidence for the close relationship between the adamellitic rocks and the anorthositic rocks is given, and a question is raised as to whether large-scale replacement might not help to explain the peculiarities of both these rock groups.

INTRODUCTION

The writer has been engaged in a study of the anorthosite and associated rocks on the Labrador coast in the vicinity of Nain for some twelve years. Though a large mass of material has been accumulated during that time, extensive areas of the intrusive rocks involved have not been examined as yet, and much work remains to be done, both in the field and in the laboratory, before any properly co-ordinated interpretation of the geology of the region can be made.

No universally accepted solution to the problem of the character and origin of anorthositic rocks has yet been proposed, and very little information is available on the large and exceptionally well-exposed Nain area. It is hoped that these facts will justify publication of the following paper, despite the incompleteness of the data and the tentative character of the conclusions reached.

All rocks are classified in accordance with the nomenclature used in Albert Johannsen's *Petrography*,[1] his definitions of the special

[1] *A Descriptive Petrography of the Igneous Rocks*, Vols. I–IV (Chicago: University of Chicago Press, 1931–39).

names within the families being accepted. However, the mineral modifiers are simply arranged in the order of increasing amount without the use of the term "-bearing"; thus hornblende-biotite granite instead of "hornblende-bearing biotite-granite." The precision of determinations is not quite so high as use of this nomenclature would suggest, since the percentage of mineral composition was estimated only by eye with a Leitz microscope having a large field of view. In many of the specimens the composition of the plagioclase was determined on the basis of refractive index, and results seem to be consistent within 3 per cent in most cases.

The graticule for the map is not constructed with accuracy, the latitude lines being no more than secants of the correct arcs. The outline of shores and drainage was fitted to this distorted grid, being reduced from the writer's original maps and British Admiralty Chart No. 265 by pantograph.

In the past the spelling of Labrador Eskimo place names on maps, as far as it has followed any system, has been largely based on a German orthography especially adapted to the Eskimo language by the Moravian missionaries. The use of *j* instead of *y*, two types of *k* which are rarely distinguished on maps, and the lack of general familiarity with the system make its use undesirable. Names incorporated on the maps from other sources are spelled according to different orthographies, and there is a good deal of confusion, even without considering obvious errors having typographical and other origins. For the sake of uniformity the writer has used the Royal Geographical System Two (R.G.S. II) throughout, even at the risk of making confusion worse confounded by introducing new spellings for some of the better-known place names.

The density of geological symbols on different parts of the map and their closeness to boundaries between groups of rocks is an indication of the relative detail with which the areas have been examined and the amount of interpolation involved in drawing the boundaries. Structural data have been indicated by the orientation of the symbols. More detailed representation is not warranted because of the lack of systematic structural observations.

The group of intermediate rocks on the map is a catch-all classification. It includes tonalite, monzonite, most of the diorite younger

than the anorthositic intrusive, and probably also some finer-grained adamellitic rocks. The lack of distinction is due to the close similarity of some coarse-grained phases of the later diorite to anorthositic rocks and to the field resemblance of finer-grained adamellitic rocks to the other rocks in the group.

ANORTHOSITIC GABBRO-DIORITE GROUP

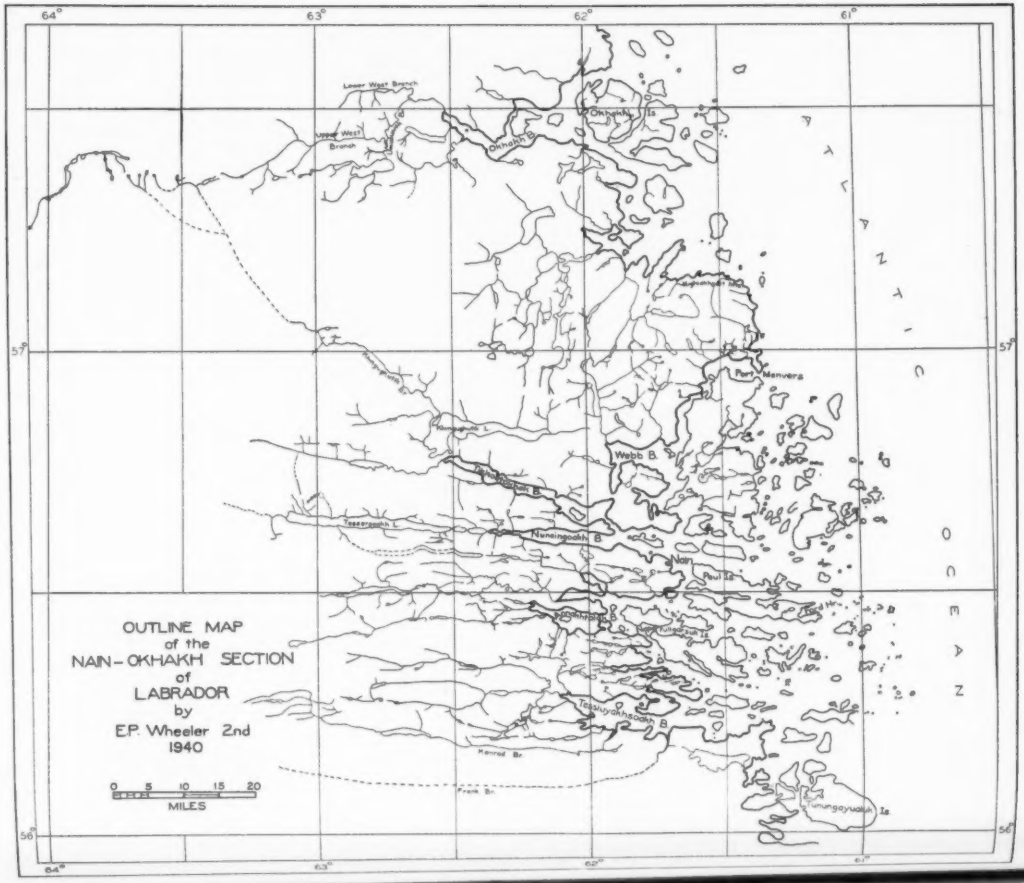
COMPOSITION

Rocks ranging from gabbro to diorite probably form the largest intrusive mass in the Nain region. They show a good deal of variation in composition, all gradations from melagabbro and meladiorite, or perhaps even perknite, to anorthosite and leucodiorite occurring. Their plagioclase content averages high, and probably there is no great bulk of rocks with more than 50 per cent of dark minerals. On the other hand, one gets the general impression in traveling through the country that there is not a great deal of rock with less than 5 per cent of dark minerals.

Chatoyant plagioclase is widely distributed, especially in the coarser, purer-feldspar rocks, though it also occurs in rocks of relatively fine grain or high mafic content. Masses as highly concentrated as that on Napartuligharsuk Island, from which came much of the material found in mineral collections, are apparently rare. It has not been encountered in the Kighlakhpait Mountain section or in the limited area examined south of the head of Okhakh Bay. Because of the great variety of composition and texture which the anorthositic rocks exhibit and because of the possibility that there are gabbros and diorites of more than one age in the region, the presence of chatoyant plagioclase has been taken as the most reliable criterion for the identification of anorthositic rocks.

The composition of chatoyant plagioclase has been found to range from labradorite (An_{58}) to andesine (An_{40}). In this group as a whole the feldspar composition has a greater variation (An_{73-35}). A few exceptional rocks which might be included in the group contain plagioclase whose composition falls even outside these limits. Within this range there are indications of a narrow gap at An_{45} and a broader one at An_{65}.

Minute oriented opaque rod and brown plate inclusions are not


64°
63°
62°
61°
57°
56°
Lower West Branch
Upper West Branch
Okhakh L.
Okhakh B.
Okhakh Is.
Port Manvers
Webb B.
Nunaingoakh B.
Nain
Paul Is.
Tessergoakh L.
Kenrad Br.
Frank Br.
Tsiunngayuaka Is.
ATLANTIC
OCEAN
OUTLINE MAP
of the
NAIN - OKHAKH SECTION
of
LABRADOR
by
E.P. Wheeler 2nd
1940
0 5 10 15 20
MILES

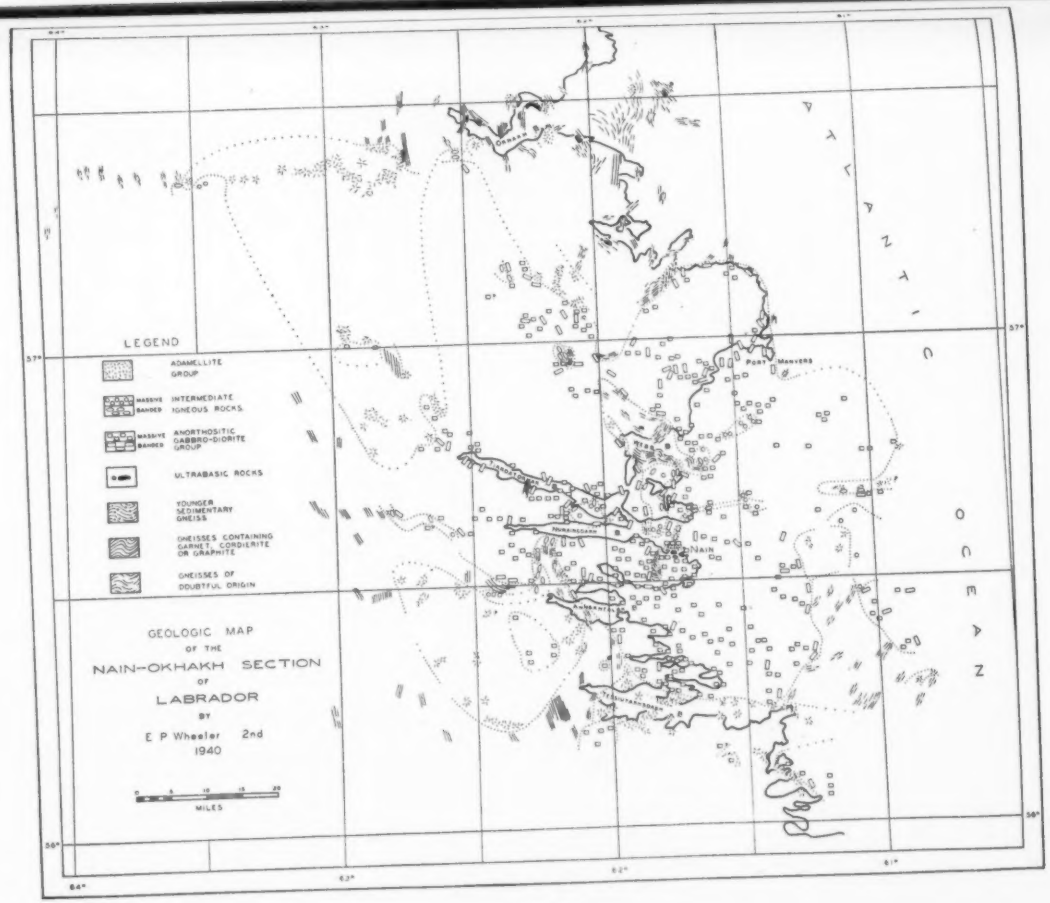

LEGEND
ADAMELLITE GROUP
MASSIVE BANDED INTERMEDIATE IGNEOUS ROCKS
MASSIVE BANDED ANORTHOSITIC GABBRO-DIORITE GROUP
ULTRABASIC ROCKS
YOUNGER SEDIMENTARY GNEISS
GNEISSES CONTAINING GARNET, CORDIERITE OR GRAPHITE
GNEISSES OF DOUBTFUL ORIGIN
GEOLOGIC MAP
OF THE
NAIN-OKHAKH SECTION
OF
LABRADOR
BY
E P Wheeler 2nd
1940
MILES
NAIN
PORT MANVERS
ATLANTIC OCEAN
64°
63°
62°
61°
57°
56°

FIG. 2

uncommon in the plagioclase of the gabbros, often being very abundant. They do not occur in all gabbros and are much less common in diorites, being rare in plagioclase more sodic than An_{45}. The darkness of the anorthositic rocks appears to be dependent on the amount of these inclusions, so that light and dark types can be distinguished. However, there are no obviously correlated differences of mafic content or texture such as those given by A. F. Buddington in his definition of the Whiteface and Marcy facies in the Adirondacks.[2]

Antiperthitic inclusions also occur in the plagioclase of this group. They are almost entirely confined to the diorites and rarely occur in plagioclase containing dark microlites. They perhaps reach a maximum of 0.05 millimeter across and show blocky sections with the traces of the best-developed straight edges parallel to the traces of the plagioclase twinning laminas. Occasional specimens also show minute antiperthitic inclusions less than 0.005 millimeter thick with spindle sections, and these can occur in the same grains containing blocky antiperthitic inclusions.

The dependence of antiperthitic inclusions and dark microlites on the anorthite content of the plagioclase points to their primary origin, either directly as contemporaneous crystallizations or indirectly as the result of exsolution. Olaf Andersen has attributed the dark microlites to the latter origin.[3] In a few specimens the central parts of plagioclase grains contain dark microlites while the margins contain blocky antiperthitic inclusions. This suggests that the formation of these inclusions is dependent on conditions in the magma from which the plagioclase crystallized and that the antiperthitic inclusions represent a later stage of crystallization than the dark microlites.

Throughout the series, monoclinic pyroxene and hypersthene are the chief mafic minerals. They commonly occur together, and either may predominate. Diorite in which only one of these pyroxenes occurs is rare, but a number of gabbros contain monoclinic pyroxene with no hypersthene. Olivine is more common in gabbro than in

[2] "Adirondack Igneous Rocks and Their Metamorphism," *Geol. Soc. Amer., Mem.* 7 (1939), p. 21.

[3] "On Adventurine Feldspar," *Amer. Jour. Sci.*, Vol XL (1915), p. 380.

diorite. It was found to have a large, negative optic axial angle wherever examined, and it is probably all ordinary chrysolite. Hornblende and biotite are rarely more than accessory minerals. Apatite is a distinctly more common accessory in diorite than in gabbro, the amount showing no obvious correlation with the mafic content. In several gabbros containing more than the usual amount of apatite there are indications of hydrothermal action, such as extensive alteration of pyroxene to amphibole and small amounts of epidote. This suggests that the apatite is introduced in these cases.

TEXTURES AND STRUCTURES

The textures in this group of rocks are as variable as their composition. They range from medium grained to very coarse, with crystals as much as 2 feet long. Some phases which may be quite coarse grained show mafic constituents which form definitely interstitial grains between blocky plagioclase crystals. Others, generally medium grained and relatively high in mafics, are markedly saccharoidal. In some rocks large, massive, poorly outlined plagioclase crystals occur in a finer-grained, often paler-colored groundmass. These large crystals are often cut by paler veins composed of plagioclase with essentially the same composition but lacking dark microlites, which may be abundant in the crystal which they cut. The veins may show excellent orientation in the crystal, occurring in several sets. A crystal cut by such veins is shown in Figure 3. Locally plagioclase forms long, thin blades with warped, parallel cleavage faces. Cleavage of big hypersthene grains sometimes shows similar warping and also steplike displacements. In thin sections gradation can be traced from rocks with excellent diabasic texture to others showing well-developed mortar structure with a groundmass mosaic of rounded, equant grains, which cut into larger, irregularly equant grains scattered through the groundmass. Among the larger grains are plagioclases with bent twinning and pyroxenes with polysomatic texture. In extreme cases these larger grains are absent. These facts indicate that the rock has crystallized with diabasic texture where not affected by stress, but that stress has commonly either destroyed this texture or prevented its formation.

Hypersthene may form thin, massive, more or less complete rims

with fluidal outlines about rounded olivine grains and run out from them in fluidal tongues. Smaller olivine grains entirely embedded in plagioclase grains have no such rims and often show well-defined crystal faces. Very delicate symplektic intergrowths, perhaps made up of vermicular hypersthene penetrating plagioclase, occasionally cut plagioclase at olivine contacts. Where massive hypersthene rims also occur, they lie between the olivine and the symplektite.

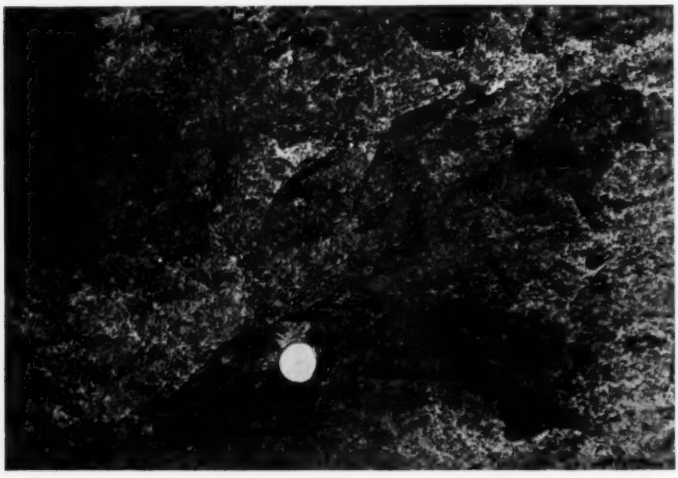


FIG. 3.—Plagioclase crystal in anorthositic rock cut by several sets of fractures along which granulation has occurred.

The coarsest facies form masses of limited extent with ill-defined margins and are often low in mafic constituents. However, individual pyroxene crystals over a foot long have been noted, and masses of nearly pure, very coarse hypersthene as much as 10 feet across have been encountered rarely. Marked irregularities in grain size, some zonal arrangement of minerals in the coarsest areas, and occurrence of massive hornblende with granitic interstitial patches and stringers in some of the coarsest masses suggest that at least a part of the excessively coarse-grained material is pegmatoid in character.

Banding is fairly common in the more mafic phases, though it is

often so faint that it can be detected only in very large exposures, such as cliffs. It is in these banded rocks that saccharoidal, rather than diabasic, texture prevails. The presence of banding is less obvious in the purer feldspar rocks as a rule, perhaps only because of the scarcity of mafic minerals to bring it out. Flow lines have been noted occasionally but do not seem to be a prominent feature of the rocks.

Block structure occurs frequently in the east part of the mass. Most of the features of this structure described by Buddington[4] were noted in this area. An occurrence on the long island about a mile north of Paul Island is of interest because blocks of banded hypersthene troctolite high in dark-gray labradorite occur in nearly massive, coarse anorthosite with light-gray labradorite and a low mafic content which appears to be chiefly hypersthene. The labradorite has a composition of An_{52}, with no appreciable difference between that in the blocks and that in the enclosing rock.

ADAMELLITE GROUP

COMPOSITION

Intrusives of the adamellite group are not so abundant as anorthositic rocks within the area examined, though they are widely distributed. They range from adamellite through granite, on the one hand, and through granodiorite, on the other. In the absence of extensive sampling and accurate Rosiwal determinations it cannot be said with certainty whether granite or adamellite predominates. However, rough estimates indicate that plagioclase constitutes over one-third of the total feldspar in a majority of specimens collected.

Orthoclase perthite is the prevalent alkali feldspar in the adamellite, and microcline perthite in the granite. In some cases the orthoclase appears to have the small optic axial angle of anorthoclase, and grains were found where the angle appeared to be variable. In these the larger angles occur near perthitic inclusions of the vein type, suggesting that there has been a recrystallization of anorthoclase with the formation of orthoclase and albite. However, the occurrence of anorthoclase needs the confirmation of more accurate

[4] *Op. cit.*, pp. 27–28.

observation, especially in view of the low birefringence and resultant poorness of optical figures in sections of the usual thickness. The plagioclase is oligoclase antiperthite with rare exceptions, generally near An_{25}. Zoning is not marked except for very thin rims of lower refraction. Monoclinic amphibole is the most prevalent mafic. Its pleochroism is generally *X*, pale yellow, and *Z*, dark green, often with a bluish shade. The blue-green variety was occasionally noted to have an optic axial angle as low as 45°. Biotite is generally present but is seldom as abundant as amphibole. However, biotite entirely supplants the other mafics in a few granite specimens. Both clinopyroxene and hypersthene are not uncommon and may be the only essential mafics. Olivine was identified by its characteristic optical properties and alteration products in thin section. Its negative optic axial angle was generally estimated at not far from 60°, indicating that it may well be fayalite. It seems mostly confined to adamellite and granodiorite, though there can be little doubt of its presence in several specimens of granite. The maximum estimated content was 7 per cent. The maximum total mafic content in these rocks was estimated at 25 per cent, and it sometimes sinks to little if any above 5 per cent. The average quartz content is 20 per cent, with a range from 10 to 40 per cent. Black ore, apatite, and zircon are nearly universal accessories, and titanite is occasionally present. Several specimens of biotite granite contain a little fluorite. Rare garnet grains associated with olivine were encountered in granite at one locality.

Where absolutely fresh, rocks of this group are often dark green. However, they discolor so readily that it is very difficult to obtain such material. Often they are badly rust stained to a considerable depth, or the surface is bleached to very pale shades and the interior is slightly rust stained. Some pink varieties occur, perhaps especially among the granites. The ease with which some of the adamellite weathers is illustrated in Figure 4.

TEXTURES AND STRUCTURES

The textural peculiarities of these rocks are the best basis for considering them to be members of a single group. The coarsest-grained phases are distinctly porphyritic with a high proportion of feldspar

grains as much as 2 centimeters across in a medium-grained groundmass. Even in the medium-grained rocks the microscope commonly shows the presence of feldspar phenocrysts, though they are not obvious in the hand specimen. Where visible to the naked eye, the phenocrysts may show a blocky tendency, though they are commonly rounded and their margins are not sharply defined. This blocky

FIG. 4.—Fresh acid garnet gneiss glacial erratic on residual pedestal of weathered adamellite resulting from more rapid weathering of unprotected adamellite.

tendency vanishes under the microscope, since the large alkali feldspar grains have margins which penetrate plagioclase irregularly and send out ragged tongues into the plagioclase very suggestive of replacement. Rounded quartz in turn cuts deeply into both feldspars. It also forms well-rounded droplets, as much as 0.6 millimeter in diameter, embedded in the feldspars. Under the binocular microscope the spherical form of these droplets is occasionally quite evident. Here they may show some indication of crystal form, but all faces are curved, with a glossy look that makes them resemble globules fused before the blowpipe. Quartz also penetrates the mafic

minerals, even olivine, with rounded lobes and tongues. Commonly there is no detectable rim between the olivine and the quartz. Intergrowths of vermicular quartz and plagioclase also occur but rarely form well-defined myrmekite nodules penetrating alkali feldspar. More commonly, the vermicular quartz penetrates portions of plagioclase grains near alkali feldspar contacts, and often features such as twin laminas can be traced from the main plagioclase grain into the area of intergrowth. Small plagioclase grains sometimes have quite blocky outlines, and alkali feldspar groundmass grains have a more normal interstitial form than the big grains.

Perthitic inclusions with spindle sections, having varying degrees of elongation and regularity, are nearly universal, at least in the larger alkali feldspar grains. They range from 0.02 millimeter across to swarms so minute that they can be detected only by the delicate mottling that their difference of refraction produces in the alkali feldspar. Perthitic inclusions of the vein type also occur to some extent, sometimes in grains which contain spindle inclusions elsewhere. Vein perthitic inclusions have not been surely identified except in microcline and seem most prevalent in granite. Here they may coalesce to form patch perthite. Coarse, irregular, interlocking perthite with the plagioclase showing twinning occurs rarely in biotite granite.

Antiperthitic inclusions are common in plagioclase, perhaps most often being absent in granite. These inclusions generally have the blocky sections characteristic of antiperthitic inclusions in the anorthositic rocks. The larger ones are often more irregular and rounded. The proportions of perthitic and antiperthitic inclusions are never so high as to raise the question of which mineral is host.

Quartz may contain minute needle inclusions oriented in several directions. Such quartz commonly has a distinctly blue color in the hand specimen.

Most of the monoclinic amphibole is massive. It generally forms rounded irregular grains. Sometimes it rims pyroxene or olivine. More rarely it also occurs as little inclusions in pyroxene with uniform optic orientation that might well be a paramorphic alteration product of the pyroxene. These relations suggest that the amphibole is derived from the other mafics, possibly as a magmatic reaction.

Some grains occur deeply embedded in alkali feldspar phenocrysts. In many of the coarser-grained rocks a poikilitic development about the other constituents can be detected.

Rocks of this group are rarely banded. In occasional specimens the plagioclase shows strain shadows, and some of the bigger grains have an irregularity of twinning that seems to indicate polysomatic texture. Perhaps there is also slight development of mortar texture. However, such phenomena are much less prominent than in the anorthositic rocks.

COMPARISON WITH OTHER AREAS

There is a striking resemblance between this group of rocks and the rocks of the Farsund-Lyngdal region in Norway. Material collected by the writer is perhaps even more like the Labrador material than C. F. Kolderup's descriptions[5] would indicate.

Granodiorite collected by C. H. Moore, Jr., in Nelson County, Virginia, in association with anorthosite appears to contain perthitic inclusions and quartz droplets similar to the Labrador material. However, extensive alteration in the Virginia rocks makes the textures less obvious.

F. F. Osborne mentions the green color of quartz mangerite and quartz diorite associated with anorthosite in the Ste Agathe–St. Jovite area of Quebec.[6]

The resemblance of the adamellite group to repakivi granite, pointed out by E. H. Kranck,[7] may be emphasized by mentioning some of the similarities. They are the occurrence of green phases; readily rusting character; the occurrence of quartz droplets, though these do not show any marked tendency to be concentrated near the margins of feldspar grains; the association of quartz and high-iron olivine; the local occurrence of fluorite; and the occurrence of coarsely porphyritic phases. Though the diagnostic orthoclase ovoids mantled with plagioclase have not been encountered, well-

[5] "Die Labradorfelse des westlichen Norwegens, I," *Bergens Museums Aarbog*, No. V (1896), pp. 112–19 and 122–30.

[6] "Petrology of the Shawinigan Falls District," *Bull. Geol. Soc. Amer.*, Vol. XLVII (1936), p. 215

[7] "Bedrock Geology of the Seaboard Region of Newfoundland Labrador," *Newfoundland Geol. Surv. Bull. No. XIX* (1939), pp. 19–20.

rounded phenocrysts occur, and there is at least an abnormal relationship between the plagioclase and alkali feldspar of the Labrador rocks.

TONALITE

Tonalite having a clearly igneous character is not abundant in the region. In general it resembles the more basic members of the adamellite series, and transitions to granodiorite occur, so that it might be considered as an end-member of the adamellite series. Possibly there is more zoning in the plagioclase of this rock than in adamellite. At least the results of refractive-index determinations are less concordant in several specimens. Pyroxenes are more commonly the dominant mafics, and the mafic content is higher. Antiperthitic inclusions generally have long, parallel, undulatory strip sections rather than the blocky sections occurring in adamellite, though the latter form, as well as small spindle sections, were noted also in a few tonalite specimens. In a number of specimens the strips are so abundant in some grains that it is open to question whether the intergrowth should be called perthite or antiperthite. Their complete absence from some plagioclase grains in these specimens and the occurrence of perthitic intergrowths of essentially similar form in the monzonite of the region increases the uncertainty. Their identification is based on the occurrence of areas in the grains, where the proportion of plagioclase decreases and its included nature becomes more evident, and on the absence of any transitions in the other direction. Quartz is very similar to that in the adamellite series, though its tendency to cut into other minerals and lie embedded in them is somewhat less marked. Where independent orthoclase grains occur, they occasionally have small tongues penetrating plagioclase. A few minute perthitic inclusions with spindle sections occur in the independent orthoclase of some specimens. Banding, bent plagioclase twinning, and mortar texture are more prevalent in tonalite than in the adamellite series.

MONZONITE

Monzonite has been found at only a few localities. Its composition is variable, so that rocks in families 10′ and 11′ as well as 10″ and 11″ probably occur. The alkali feldspar is orthoclase perthite.

Plagioclase is quite acid, ranging from An_{20} to An_{35}, and perthitic inclusions seem to have about the same composition. Clinopyroxene is generally the chief dark mineral. It is nearly colorless in thin section, and its optic axial angle is moderately large. Hypersthene, with little color in thin section, often accompanies clinopyroxene and is rarely the only pyroxene. Hornblende with $2V$ large and pleochroism in shades of brown is generally present and may be the principal mafic. Olivine is always present in small amounts. It has the relatively small negative optic axial angle of a high-iron variety, and a grain separately from one specimen proved to have refractive indices distinctly above 1.776. It shows typical alteration to serpentinous material in some specimens. Accessory black ore, apatite, and zircon are always present. Titanite also occurs in several specimens.

Perthitic inclusions are variable in form. Some have parallel spindle sections 0.003 millimeter and less across. Others have spindle or blocky sections as much as 0.05 millimeter across, and these may be elongated to form slightly undulatory parallel strips. Where both types occur in the same grain, there is a marked gap between them in size. In some grains the larger inclusions are so abundant that it is difficult to determine that the orthoclase is the host mineral, but transitions between these doubtful grains and unquestionable perthite can generally be found. Blocky antiperthitic inclusions are rare or absent.

Hornblende shows forms similar to those of amphibole in adamellitic rocks, except for the absence of poikilitic development in the monzonite. Thus its origin is probably the same as in the adamellitic rocks.

The monzonite is generally medium grained but can be quite coarse. Banding is commonly present, and there is often a mosaic of smaller, rounded grains between the larger ones.

Except for the universal presence of olivine, this rock shows a noteworthy similarity to mangerite. It has the variable composition suggested for that rock by Johannsen,[8] and the same textural peculiarities.

[8] *Op. cit.*, Vol. III (1937), p. 63.

DIKE ROCKS

Small gabbro dikes are rare in the region. Those encountered are seldom over a few feet wide, are fine grained, and have a high mafic content with accessory apatite. Those cutting anorthositic rocks may have both rhombic and monoclinic pyroxene as the chief mafic minerals, though hornblende can be a major constituent or even largely take the place of pyroxenes. Some have a high content of black ore which may be concentrated near the margin. They contain little biotite and are essentially massive. A few were noted cutting gneisses adjacent to the gabbro-diorite intrusive. These generally contain biotite in addition to pyroxenes or hornblende as an essential constituent. They show marked foliation and saccharoidal texture.

Diorite dikes are much more prevalent than gabbro. Some are so large that their dike form is not evident. Their texture seldom exceeds medium-fine grain. They are often high enough in pyroxenes to approach meladiorite. Biotite is not abundant. Plagioclase commonly has a composition near An_{30}, but dikes with more calcic plagioclase occur. Antiperthitic inclusions are prevalent but do not always occur. These inclusions generally have blocky sections but some have spindle sections. Some dikes show the latter type exclusively, but some contain both types together. Banding, accompanied by bent feldspar twinning and mortar texture, may be present. Some dikes contain cognate inclusions, which may be of several generations that differ very little in composition or texture but are banded in different directions. Some larger masses of diorite which seem to have dike form are so coarse grained and low in mafics that they approach the anorthositic rocks in appearance. However, they commonly contain antiperthite of the strip type with a high proportion of plagioclase similar to that in tonalite and rust more readily than the anorthositic rocks. A single dike resembling the finer-grained diorite dikes, but containing olivine as an essential constituent, was found.

Small dikes occur with the composition characteristics of the large masses of the adamellite group, even to the association of quartz and olivine in some cases. The texture of these dikes is also similar, though coarsely porphyritic phases do not occur, and perthitic in-

clusions may tend more generally to cryptoperthitic proportions. In these smaller dikes, banding with bent feldspar twinning and mosaic texture are occasionally evident.

In some places tonalite forms definite small dikes. These show no marked differences from the larger masses in composition or texture except for the more common occurrence of strip-type antiperthite with a high plagioclase content. In some specimens this antiperthitic intergrowth is so irregular that its form suggests that of myrmekite.

All these dike rocks are readily distinguishable from diabase in the field because they lack distinctly chilled margins. The diabase dikes have been treated in considerable detail elsewhere.[9] Pegmatite dikes have not been studied in any detail, though they are quite abundant in all the major rocks of the region. Perhaps the most prevalent type in the igneous rocks is leucogranite with pink or white alkali feldspar, which may show microcline twinning, at least locally, and is generally badly clouded by secondary material. Perthitic inclusions, commonly of the vein type, are prevalent. Dark constituents are chiefly biotite or chlorite which appears to be derived from it. Epidote is also present in some cases. Dark grains in quartz occasionally are surrounded with the radiate fractures characteristic of allanite, and such grains have optical properties which are not at variance with those of the alteration products of allanite. Such dikes are generally not more than a few feet thick, coarse to very coarse grained, and show the localization of constituents characteristic of pegmatite.

These dikes sometimes seem to be associated with, or grade over into, medium-grained pink granite with a low mafic content including both hornblende and biotite. One of these finer-grained dikes was determined to be sodaclase-granite, family 216 near 116, with microcline. It has textures resembling those of granite in the adamellite series. Other dikes in this group have the more granular appearance of aplite.

A much less common type is made up of dark-red feldspar, ap-

[9] E. P. Wheeler, 2nd, "A Study of Some Diabase Dikes on the Labrador Coast," *Jour. Geol.*, Vol. XLI (1933), pp. 418–31.

parently with graphic intergrowths of quartz and with a very low mafic content.

Tonalite and leucotonalite types are not common but are of especial interest because of their similarity to anorthositic rocks, which they resemble closely in appearance except for the presence of quartz. Their feldspar is antiperthitic andesine with a composition near An_{35}. In one specimen it appears to vary from An_{22} to An_{45}. The quartz commonly has a violet tinge in the hand specimen. In some dikes the mafic content approaches 40 per cent, while in others scarcely any dark minerals are present. Both clinopyroxene and hypersthene may be present, or hypersthene may occur alone. Biotite, chlorite, and hornblende with *Z* blue-green may occur, but at least the last two appear to be derived from pyroxene. These dikes are never more than a few feet across. Their coarse grain indicates their pegmatitic nature. Some dikes whose appearance resembles these closely in the field appear to contain no quartz.

A few pegmatoid granide dikes contain a pale-green feldspar that looks like amazonite.

ULTRABASIC ROCKS

Nearly all the ultrabasic rocks in the region contain orthopyroxene, and most of them contain olivine, clinopyroxene, or hornblende as essential constituents. Various combinations of these minerals occur, and any one of them may be the most abundant. Biotite is not common and was found as a major constituent in only one specimen. Small amounts of plagioclase are sometimes present. Black ore is generally present in small amounts. Some specimens contain occasional small grains of green spinel, which is rarely accompanied by small, dark-brown, isotropic grains that might be chromite or spinel.

The optic axial angle of the orthopyroxene is commonly so large that it is impossible to say whether it is enstatite or hypersthene. In thin section it is either colorless or very faintly colored, with pleochroism from pink to green. Where refractive indices of olivine were determined, they indicate that it is chrysolite with a molecular content of Fe_2SiO_4 not far from 15 per cent, and in all cases the optic axial angle is not far from 90°. Plagioclase is more calcic than that in

the anorthositic rocks, being acid bytownite in most cases. Hornblende is massive and pale green in most thin sections, though a rare slide contains a dark-brown variety.

These rocks are medium grained with rounded interlocking grains, olivine being most automorphic and hornblende least so. Where the pyroxene content is high, the grains seem to have a trace of blocky crystal form. The rocks show banding in the field, though this is rarely well enough developed to be evident in the hand specimen.

As a rule all the constituents of these rocks are notably fresh, and even where olivine is associated with plagioclase there is no reaction rim at their contact. Rarely serpentinous and talcose minerals are abundantly developed. Soapstone occurs locally in the region associated with rocks of this character and is probably the result of their hydrothermal alteration.

One exceptional rock belonging to this group is composed of olivine with a large amount of ilmenite and a little apatite. The olivine has a quite large negative optic axial angle, but alpha is slightly above 1.751, suggesting roepperite.

Melagabbroic types occur, whose relation to the ultrabasic rocks is indicated by the identity of their mineral constituents and textures, though the content of calcic plagioclase, in one case An_{93}, may rise to as much as 30 per cent.

The ultrabasic rocks are widely distributed through the area but never form extensive masses. They occur most commonly in the older gneisses but have also been found in the anorthositic rocks. In the gneisses they occur either as well-defined bands or as fragmental masses whose banding is cut off by the enclosing gneisses. Similarly, in the anorthositic rocks, banding in larger masses of ultrabasic rock may be cut off at contacts with the intrusive rock, though there is a tendency for banding to approach parallelism in the two. Certainly some of the small masses in the anorthositic rocks are fragmental with broken banding.

The prevalence of chrysolite in these rocks is indicative of an igneous origin, but their often fragmental character is difficult to explain on the basis of their being intruded. They would be more satisfactorily explained as skarn rocks if olivine can form in skarn. Intimate injection of skarn rocks by the anorthositic intrusive

would account for the highly calcic character of the plagioclase and the sharp variation in its composition over short distances, observed in some of the marginal melagabbroic gneisses. It would also explain their melanocratic character.

The local occurrence of pyrrhotite in rocks of this character associated with anorthositic rocks is in accord with this interpretation.

GNEISSES ASSOCIATED WITH THE IGNEOUS ROCKS

The gneisses associated with the igneous rocks of the region have not been sufficiently studied to permit a detailed discussion. The highly banded gabbroic and dioritic gneisses have compositions closely resembling the various anorthositic rocks, even in the occasional presence of olivine. They are a good deal more melanocratic as a rule, melagabbroic and meladioritic gneisses being quite common. The chief mineralogic difference is the general presence of massive brown, or more rarely brownish-green, hornblende. It may largely take the place of pyroxenes, but there is evidence that it is derived from them. Dark rod microlites occur in the plagioclase of a few specimens, but no antiperthitic inclusions were found. The anorthite content of the plagioclase often varies sharply over short distances and is very high in some of the melagabbroic gneisses.

Gneiss of this character is best developed near the margins of the anorthositic intrusive and in the gneiss zones within the mass. Most of it has been considered to be marginal facies of the anorthositic intrusive and mapped as part of that body because of the spatial relations and the resemblances in mineral composition. However, no satisfactory transition zones between the gneisses and the more obviously igneous rocks have been found, and essentially identical rocks occur as bands in the gneisses a good many miles from the nearest known outcrops of anorthositic rocks.

Most of the gneisses are a mixture of light and dark bands in varying proportions. Where the light bands predominate, the dark bands are often fragmental. Although biotite and hornblende are commonly the chief mafics, there are large areas, found mostly near the anorthositic intrusive, where both monoclinic and rhombic pyroxenes are widely distributed and may be the chief mafics, even in the more acid rocks. This appears to be in marked contrast to the

gneisses farther south around Hopedale, where pyroxene has not been found in the few thin sections examined.

The light gneisses are commonly gray, and if the material collected is representative of the area as a whole they are most commonly tonalitic or adamellitic. Granitic gneisses are less abundant, though granite pegmatites are common and intrusive granite occurs. Perthite and antiperthite are common in the light-gray gneisses, and this, taken in conjunction with their locally transgressive contacts, indicates their intrusive nature. Quartz and alkali feldspar drop out altogether in the darker gneisses. Their plagioclase is more calcic, and no antiperthitic inclusions occur. The older gneisses in the section from outside Tessiuyakhsoakh Bay to Qkhakh Islands resemble the igneous rocks of the region very closely in composition and even in texture, except for their highly banded character and finer grain. If they contain a sedimentary component, it has been so thoroughly altered by the igneous component that its original character is not evident. The same is true of the gneisses about the source of Khingughutik Brook and to the west. In this last region there is possibly more pink granitic gneiss, and garnet occurs rarely. The gneiss masses enclosed by the anorthositic intrusive have an equally indeterminate character. On the whole, they are darker than the gneisses surrounding the intrusives.

On Okhakh Islands garnet occurs occasionally. Toward the head of Okhakh Bay it becomes more abundant, and graphite is occasionally encountered, indicating that the gneisses have a sedimentary component. Around Umiakovik Brook gneisses high in biotite with a good deal of garnet and graphite become prevalent, indicating that they are in large part of sedimentary origin. Garnet is also prevalent in the gneisses about Konrad Brook and in the section from the big lake on that brook northward to the region west of Khingughutik Lake. The occurrence of a thin band of impure marble in this gneiss zone on Tessersoakh Lake and of graphite about the head of Tessiuyakhsoakh Bay indicates that these gneisses contain a sedimentary component at least. On Tessersoakh Lake some of the most acid garnet gneiss is adamellitic with microcline perthite. Locally this rock is coarser grained than average, suggesting pegmatitic development, and some of its margins are trans-

gressive. Thus it appears to be of igneous origin, the garnet very likely resulting from contamination by the sedimentary portion of the gneiss. Some of the hypersthene tonalitic gneiss and hypersthene adamellitic gneiss toward the head of the lake has quite excellent linear flow structure. Garnet is rare in the gneisses within the area of the anorthositic rocks but occurs sparingly in the zones south of Tikkoatokhak Bay and Nunaingoakh Bay.

Cordierite is quite abundant, and garnet occurs in the gneiss belt caught between the anorthositic and adamellitic intrusives west of the head of Annakhtalak Bay. Cordierite also occurs in the mass of gneiss on lower Khingughutik Brook, whose relation to the anorthositic and adamellitic intrusives may be similar. Thus these masses of gneiss are probably contact-metamorphosed aluminous sediments. Small amounts of cordierite also occur rarely in the gneisses adjacent to the anorthositic intrusive on the north shore of the Kiglakhpait Mountains.

A narrow belt of gneiss along the northwest margin of the anorthositic intrusive lobe at the Kiglakhpait Mountains has a distinctly different character from the foregoing gneisses. Here distinct beds of quartzite—some of them impure and containing garnet—and beds with readily discernible conglomerate pebbles occur. Thick, dark, fine-grained beds associated with these silicious beds are probably metamorphosed basic sediments and contain abundant graphite in some cases. This series is evidently of sedimentary origin. The well-preserved character of the original sedimentary features, the relatively open folding of the formation, and the lack of intimate impregnation with igneous material mark it as distinctly younger than the other gneisses of the region.

AGE RELATIONS

The presence of olivine in anorthositic rocks, even near the margins of the intrusive, indicates that they have not been subjected to any great degree of dynamic stress since their consolidation. Though massive hypersthene and delicate symplektic intergrowths rim olivine in some cases, they are neither universally present nor developed on a large scale. The theory that such textures are exclusively the result of regional metamorphism is not universally ac-

cepted;[10] and, in view of the common occurrence of typically igneous, diabasic textures in the intrusive, there does not seem to be sufficient evidence that it had consolidated before the last period of marked pre-Cambrian dynamic metamorphism in the region. The massive pyroxene rims might be accounted for as magmatic reactions, and the symplektic intergrowths as end-stage reactions or products of emanations from the pegmatite dikes which cut the intrusive.

If these conclusions are correct the anorthositic intrusive must be younger than the highly metamorphosed, more or less granitized gneisses of the region, which are probably of Archeozoic age. Likewise, they appear to be younger than the less metamorphosed sedimentary series adjacent to the anorthositic rocks at the west end of the Kiglakhpait Mountains, since even these are sufficiently metamorphosed for the formation of garnetiferous quartzite. However, no unmistakably intrusive contacts have been found between the anorthositic and the metamorphic rocks to corroborate this view.

A. P. Coleman has suggested that sedimentary rocks showing a degree of metamorphism similar to that of the younger metamorphosed sediments of the Kiglakhpait region and also containing conglomerate members with "metamorphosed sandstone" at Pomiadluk Point may be of Sudburian age.[11] Kranck assigns these rocks, which he calls the "Aillik formation," to the Timiskaming.[12]

The diabase dikes, which cut the anorthositic rocks, are the only younger rocks encountered in the region for which even a tentative age correlation can be made. Coleman has suggested that such dikes may be older than the Ramah series, which he tentatively assigns to the Huronian.[13] He bases his judgment on the more ancient appearance of the diabase dikes examined by him, compared with those of northern Ontario, and the fact that no diabase dikes have been found extending up into the Ramah series. On this basis, the anorthositic intrusion might have taken place at about the time of the Algoman revolution.

However, olivine diabases cutting anorthositic rocks are quite

[10] Buddington, *op. cit.*, p. 325.

[11] "Northeastern Part of Labrador, and New Quebec," *Canada Geol. Surv., Mem. 124* 1921), p. 24.

[12] *Op. cit.*, p. 32.

[13] *Op. cit.*, pp. 24–25.

fresh, and, as inferred by Kranck,[14] in a region where so little detailed geologic work has been done failure to find diabase dikes cutting the Ramah series is not conclusive evidence that none exist. Both olivine diabases and quartz-bearing diabases were found cutting the anorthositic rocks. The latter diabases are more extensively altered than the former, though no direct evidence of their age relations has been found. This association is similar to that described by E. S. Moore in eastern Canada[15] and lends weight to the idea that the diabases cutting the anorthositic rocks may have been intruded during the same period of igneous activity. Moore considers this activity to have begun in lower Keweenawan time. On this assumption the tentative time of intrusion of the anorthositic rocks must be extended to include the interval between Sudburian and Keweenawan time.

A short distance northwest of Nain, biotite-olivine hyperite forms a mass at least several miles long. It has been mapped as part of the anorthositic intrusive. However, its quite uniform, finer grain size, its higher mafic content, including biotite, and the entire absence of chatoyant feldspar make easy its separation from the anorthositic rocks of the section. At one place near its margin there is a decrease of grain size, suggesting chilling or marginal granulation, and it may be a later intrusive, perhaps even entirely unconnected with the anorthositic intrusive.

The prevalence of olivine in the ultrabasic rocks of the region and the absence of any reaction rims about it, even where in contact with plagioclase, indicate that these rocks also were formed subsequent to any extensive dynamic metamorphism in the region. Since they occur as fragmental inclusions in the anorthositic rocks, they must be older. On the assumption that they are skarn rocks, this would indicate that they were formed by emanations from the anorthositic intrusive.

The highly mafic gabbro dikes which cut the anorthositic rocks are old, as indicated by their being cut by pegmatite dikes. Apparently similar dikes are also cut by olivine-pyroxene adamellite.

[14] *Op. cit.*, p. 6.

[15] "Keweenawan Olivine Diabases of the Canadian Shield," *Trans. Roy. Soc. Can. Sec. IV*, Vol. XXIII (3d ser., 1929), pp. 39–45.

The often sinuous form of the gabbro dikes suggests that they may have been intruded soon after the anorthositic rocks consolidated. The more or less foliated gabbro dikes cutting adjacent gneisses may be of the same age, both being basic differentiates of the magma from which the anorthositic rocks consolidated. However, no evidence has been found beyond the close association with anorthositic rocks to demonstrate that the foliated dikes are not older. They have been found cutting the younger metamorphosed sediments of the Kiglakhpait region; and, if they can be demonstrated to be related to the anorthositic intrusive, this would be direct evidence that the sediments are older.

Since diorite dikes cut anorthositic rocks and contain anorthositic inclusions, they must have been intruded after the anorthositic rocks were at least locally consolidated. However, the mineralogical similarity between the dikes and some phases of the anorthositic rocks, and the absence of markedly chilled margins in the diorite dikes suggest a close relationship to the anorthositic rocks. At least they are older than diabase, which has been found cutting them.

Rocks of the adamellitic series cut anorthositic rocks and occur as dikes in them at a number of places. In turn they are cut by diabase dikes so that their age must be intermediate between the two. Since tonalite was found marginal to adamellite and apparently grading into it, the tonalite may be a marginal facies of the adamellitic intrusive. However, dikes of tonalite as well as adamellite occur cutting anorthositic rocks, indicating that they are capable of independent intrusion. Also an outcrop of hornblende adamellite or granodiorite contains cognate inclusions of finer-grained, more mafic, porphyritic adamellite not far from Archeozoic gneisses. These cognate inclusions probably represent a marginal facies of the intrusive and indicate that alkali feldspar may increase rather than decrease near the margin of the adamellite.

Monzonite is younger than the anorthositic rocks, fragmental inclusions of which occur in it. Since monzonite is associated with adamellitic rocks at a number of places and rocks intermediate between the two seem to occur, there is a possibility that monzonite is another phase of the adamellitic intrusive. At the big island in Tikkoatokhak Bay, monzonite is cut by a small olivine diorite dike,

but this is the only diorite dike in which olivine was found. Thus there is a possibility that it has a different origin from that of most of the diorite dikes in the region and is not necessarily of the same age.

On the south side of the biggest lake of Umiakovik Brook, pink biotite granite with pegmatoid facies and containing fluorite shows intrusive relations toward the gray, often rusted, adamellitic rock of

TABLE 1

Algonkian	Quartz-bearing diabase dikes and olivine diabase dikes with chilled margins
	Adamellitic series, perhaps with tonalite and monzonite facies, accompanied or followed by pegmatites
	Younger diorite?
	Anorthositic gabbro-diorite series, probably accompanied by pegmatite
Sudburian	Moderately metamorphosed conglomerate, sandstone, and basic sediments
Archeozoic	Highly metamorphosed gneisses with a variable component of sedimentary material

the region. It does not differ materially from more acid members of the adamellite series and may well be a final differentiate of the series. Small independent granite bodies about Okhakh Islands and Okhakh Bay have a similar composition and texture, and some of them contain the bluish quartz sometimes found in the adamellitic rocks, indicating that they also belong to the adamellite group.

Pegmatite dikes have been found cutting practically all the rocks in the region, except diabase, so that at least some of them are younger than the adamellitic rocks. It is quite probable that older pegmatites occur connected with the intrusions preceding the adamellitic rocks.

These tentative age relations are outlined in Table 1.

STRUCTURAL RELATIONS

Evidences of the primary nature of the banding in the igneous rocks of the region are: the presence of banding in block-structure fragments of the anorthositic rocks and in the cognate inclusions of the later diorite, which differs in character or direction from the banding in the enclosing rock; bending of banding about anorthositic inclusions in tonalite and monzonite; and the presence of olivine in highly banded rocks. Since increased intensity of banding in these rocks is generally accompanied by increase in the development of textures indicating crushing, the crushing is probably protoclastic.

Banding is often quite well developed near the margins of the anorthositic intrusive, where it is in contact with gneiss and shows a tendency to strike parallel to the contact. This distribution becomes still more pronounced if these melanocratic gabbroic and dioritic gneisses which are adjacent to the more obviously igneous rocks are considered as part of the intruded mass. Except for the Kighlakhpait lobe of the intrusive, the banding dips away from the anorthositic mass at quite steep angles as a rule. On the assumption that this structure tends to parallel the walls of the intrusive, it indicates that the body is, in general, steep walled and has a section which increases in size downward.

The conditions are notably different on the north and east sides of the Kighlakhpait lobe. Here, exceptionally well-developed and uniform banding, though striking parallel to the margin, dips into the mass at low to intermediate angles. This banding is accompanied by well-developed jointing with the same strikes but complementary dips. Both these features indicate that in this region the intrusive has a floor dipping under it. A contact of this character actually seems to be exposed on the north shore of the Kighlakhpait Mountains, as shown in Figure 5. Even at this excellent exposure a definite surface of contact is not evident. This would indicate that, if it is an intrusive contact, the igneous rocks have not cut the enclosing rocks sharply but have penetrated them to form a mixed gneiss zone. The exceptional ilmenite dunite mentioned under the ultrabasic rocks forms thin bands parallel to the general banding at Port Manvers. They may be flow bands composed of early crystalliza-

tions from the magma, concentrated near the floor of this lobe by gravity.

The anorthositic rocks show little banding where they are cut by the adamellitic intrusive north of Tessiuyakhsoakh Bay. This would be expected if the banding in the anorthositic rocks is best developed as a primary marginal feature and the apparently isolated masses of

FIG. 5.—North-shore point of the Kiglakhpait Mountains viewed from the east, showing hypersthene tonalitic gneiss underlying banded gabbro. Contact zone indicated by arrows.

anorthositic rocks to the south are parts of the main mass of anorthositic rocks, which have been cut off by the adamellitic intrusive. Where adamellitic rocks lie between more strongly banded anorthositic rocks and gneiss in other parts of the area, it is possible that the adamellitic rocks have been intruded near the original margin of the anorthositic mass.

Even far from the margins of the anorthositic mass, banding is not uncommon, though it is seldom strongly developed. Such banding often has moderate or even steep dips. However, there are enough areas where it is quite flat to suggest the proximity of a top or bottom contact, when taken in conjunction with its distance from a

margin. Since there appears to be a tendency for marginal banding to dip from the intrusive mass toward the margins and toward gneiss inliers, the proximity of a roof seems the more likely alternative for the intrusive as a whole, despite the quite strong evidence of a floor in the Kighlakhpait Mountain lobe. Thus, the gneiss masses within the area of anorthositic rocks may be roof pendants, and the anorthositic masses which are apparently separated from the main body by gneisses may be cupolas connected with it at depth.

Refractive-index determinations on the plagioclase of anorthositic rocks indicate that there is a regional localization of plagioclases with different composition, the composition being quite uniform over considerable areas. Since dark microlites are most prevalent in the more calcic plagioclase and since their amount is apparently responsible for the darkness of the feldspar, the localization of feldspars with different compositions is reflected by a localization of dark and light phases of the anorthositic rocks. The relative darkness of the anorthositic rocks would indicate that the more calcic plagioclase predominates on the east and north sides of the intrusive, while less calcic plagioclase predominates in the center and on the west. Refractive-index determinations corroborate this conclusion, where they have been made. There are numerous exceptions, and much of the rock is so indeterminate in color that it cannot be assigned to either group. The absence of dark microlites from the matrix of crushed rocks, though they may be plentiful in the enclosed residual grains, indicates that they are destroyed by crushing, and this may account for some of the irregularities in distribution of the light and dark phases. On the whole, the evidence indicates a concentration of the less dense, later-crystallizing, more sodic plagioclase toward the roof of the intrusive, while the heavier, earlier-crystallizing, more calcic plagioclase is concentrated toward the floor. Such a condition would be expected if differentiation by crystal settling had been effective during the consolidation of the anorthositic intrusive.

The attitude of banding in the monzonite, tonalite, and younger diorite proved to be parallel to their margins wherever these could be located, and there is no indication that this condition is not general. Banding is absent from most of the adamellitic rocks, except in some finer-grained exposures that might be marginal crushed

rock. Here again what evidence is available points to its being parallel to the margins.

The banding of the gneisses in the region has a quite uniform strike which approaches north-south at a distance from the intrusives, the dips being steep but variable. Near the intrusives the attitude becomes erratic, indicating that the gneisses have been thrust aside by the intrusives. Possibly this accounts for the irregularity of banding in the gneisses near Okhakh Islands. Though there are no major intrusives outcropping in that area, there are quite a number of small biotite-granite bodies which have been tentatively correlated with the adamellite series and which have penetrated the gneisses more or less intimately.

DEPTH OF INTRUSION

The indefiniteness of contacts between anorthositic rocks and the intruded gneisses and the bending aside of the gneiss banding from its regional trend in the vicinity of the intrusive rocks indicate that they were emplaced at considerable depths. The coarse grain of adamellitic rocks and of even the nonpegmatoid parts of the anorthositic intrusive points in the same direction. The finer-grained margins of the intrusives are interpreted as the result of protoclastic crushing rather than of chilling produced by intrusion at slight depth. However, no convincing evidence can be adduced to refute a contrary view. Marked fracture cleavage in gneiss at some contacts with anorthositic rocks and the blockily irregular contacts of some adamellitic dikes cutting anorthositic rocks indicate that the intrusives were not emplaced at extreme depths.

RELATIONSHIP BETWEEN ADAMELLITIC AND ANORTHOSITIC INTRUSIVES

The association of anorthositic rocks with adamellitic rocks having similar peculiarities is so common in various parts of the world that it must be more than a fortuitous circumstance. The fact that olivine occurs in both these rock groups at one locality, as in the Nain region, while it is absent or very rare in them both at another locality, as in the Egersund region of Norway, emphasizes the close relationship between the groups. The increased iron content of the

olivine in the more acid rocks of the Nain region indicates that it is a differentiation product rather than included foreign material.

The available data are not sufficient to account for the association of these two rock groups in the Nain region on the basis of a filter-press theory of differentiation, such as that proposed by Robert Balk for the association in the Adirondacks.[16] By the nature of the filter-press process, the expressed residual magma becomes an intrusive magma; and the rock which forms from it will show intrusive relations toward any rock with which it is in contact, when it consolidates. Thus, its origin will be detectable only on the basis of extremely detailed chemical and structural data, if it can ever be demonstrated beyond a reasonable doubt.

There is good evidence that the adamellitic rocks are younger than the anorthositic intrusive in the Nain region, and other writers have reached the same conclusion about the order of intrusion of these two groups in other areas. The blocky character of adamellite dikes in anorthositic gabbro even points to a considerable interval between the two intrusions. Yet the evidence of close relationship between the two rock groups suggests that they both belong to a single period of igneous activity. The less pronounced development of flow structures in the adamellitic rocks as compared with the anorthositic rocks may be taken to indicate that they were both intruded during a single period of waning stress. However, simplicity of theory and consonance with the idea that the two groups are closely related are the best supports for this interpretation.

In the adamellitic rocks the prevalence of perthite and antiperthite, the uncommon association of olivine and quartz, and the unusual textural relations between alkali feldspar, quartz, and plagioclase point to very peculiar conditions at the time of consolidation. It seems possible that the correct interpretation of these features and the determination of the conditions under which they were produced may prove an important step toward a solution of the anorthosite problem. To the writer they suggest the activity of volatile constituents, perhaps only because it is easy to assign in-

[16] "Structural Geology of the Adirondack Anorthosite," *Min. Pet. Mitt.*, Vol. XLI (1931), pp. 411–13.

explicable phenomena to an agency whose potentialities are little known but may be great.

If the adamellitic rocks can be correlated with rapakivi granite, there is at least a regional association of anorthositic rocks and rapakivi granite in Canada and Scandinavia. The anorthosites have a composition which is not easily interpreted by the known principles of igneous geology, and the rapakivi granites have textural peculiarities which are equally difficult to explain by those principles. H. G. Backlund explains the rapakivi granites as large-scale replacements of silicious sediments, accompanied by fusion under certain conditions.[17] This prompts the speculation that the anorthositic rocks might be the result of some similar process—a possibility to which Backlund himself calls attention.[18]

ACKNOWLEDGMENTS.—The writer is deeply indebted to Professors C. M. Nevin and J. D. Burfoot for much discussion, encouragement, and help in this work. A National Research Council grant-in-aid provided the funds for cutting many of the thin sections used in this study.

[17] "The Problems of the Rapakivi Granites," *Jour. Geol.*, Vol. XLVI (1938), p. 339.

[18] *Ibid.*, p. 383.

GROUND TILT AT KILAUEA VOLCANO

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ABSTRACT

Ground tilt has been measured daily for twenty-seven years at the Hawaiian Volcano Observatory, Hawaii National Park. A brief discussion of instrumental measurement of tilt is given. Resultant tilt has been computed for the entire record and is shown as a general chart. Resultant tilt for individual years with volcanic outbreaks is shown. Tilt represents deep-seated pressure changes and is correlated with volcanic activity and with ground-level changes. Local loading affects tilt but slightly.

INTRODUCTION

Early studies of volcanic eruptions and earthquakes in Japan drew attention to ground tilt as a factor of great importance preceding, during, and after the respective disturbances. The pioneer in tilt studies in that country was the late Professor Omori; and the work which he started has been ably continued. In 1930 Imamura[1] discussed at length "Topographical Changes Accompanying Earthquakes or Volcanic Eruptions."

In that publication are considered fourteen earthquakes between the Tosa earthquakes of the year A.D. 684 and the Formosa earthquake of 1905, with which ground tilt is known to have occurred but where no instrumental check was available. Tilt changes of twelve other earthquakes between 1891 and 1927 were checked by precise leveling. In addition tilt changes associated with the volcanic eruption of Usu in 1910 and the Sakurajima eruption of 1941 are described. One of the principal conclusions was that with nearly all earthquakes and all volcanic eruptions there occur topographic changes (with emphasis on grount tilt) whether they are observed or not. This conclusion has served only to emphasize the importance of tilt studies already in progress and the development of instruments for determining tilt to supplement data from other geophysical investigations. The results may be of great value in predicting future

[1] Akitun Imamura, *Pub. Earthquake Investigation Comm. in Foreign Languages, No. 25*, 1930.

earthquakes or volcanic eruptions. The Japanese seismologists have developed a wide variety of tilt-measuring devices and are obtaining data in quantity from both volcanic and seismic areas, with most attention probably centered on the Tokyo area, scene of the very destructive Kwanto earthquake of September, 1923. Results have proved instructive and encouraging and undoubtedly, as more knowledge is gained, will play an important role in predictions both volcanic and seismic.

The Hawaiian Volcano Observatory, located 2.2 miles northeast of the center of Halemaumau and 1.4 miles northeast of the center of Kilauea crater (Fig. 1) was established in 1912 at a time when there was an active lava lake in Halemaumau. As a result, observations were concentrated on the visible manifestations. But it was soon discovered that unseen movements and disturbances under volcanoes are probably of as much, if not of more, importance than the more obvious ones seen on the surface. Seismographs had been installed and their operation maintained from the very beginning of the work; and it was discovered that the recording pens made systematic changes of position on the recording drums which were apparently caused by ground tilt. This tilt at the Volcano Observatory was measured daily and plotted. However, tilt was not given an important place in the study of Hawaiian volcanoes until 1917, when Arnold Romberg and T. A. Jaggar began the systematic recording and studying of daily tilt changes and their relationship to Kilauea and Mauna Loa. Jaggar and R. H. Finch[2] extended the study to seasonal tilt and long-term accumulation by showing north-south and east-west tilt separately. Today it is an important part of the regular routine and appears to be one of the most reliable indicators of volcanic changes. This is especially true at times like the period from 1924 to the present, during which Halemaumau has had only a few brief periods of visible activity.

METHODS OF MEASURING TILT

Tilt has been defined by Jaggar and Finch[3] as "a change in the angular relation between a portion of the earth's surface and the

[2] "Tilt Records for Thirteen Years at the Hawaiian Volcano Observatory," *Seis. Soc. Amer. Bull.*, Vol. XIX, No. 1 (March, 1929).

[3] *Ibid.*

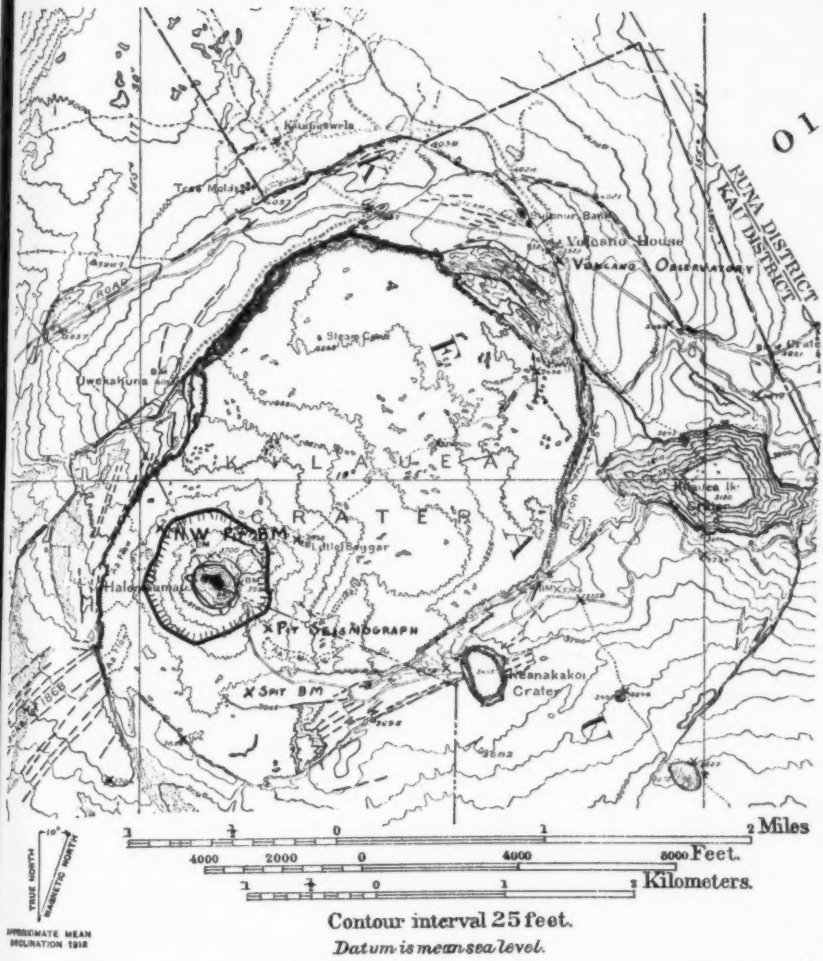

FIG. 1.—Kilauea Crater, Hawaii National Park, showing location of tilt stations. (From U.S. Geological Survey special map of the proposed Kilauea National Park, advance sheet.)

plumb line." This change is measured on "tilt-sensitive" seismographs or on clinoscopes built especially for tilt measurement. Horizontal pendulums of several seconds period are particularly tilt sensitive, with sensitivity increasing in proportion to the square of the period. At Kilauea the Bosch-Omori seismograph located on the rim of Kilauea crater is the principal instrument used for tilt determinations. In addition there are two clinoscopes within Kilauea crater, one on the southeast rim and the other on the west of Halemaumau. For other tilt studies values are also obtained from the Mauna Loa, Hilo, and Pit seismographs.

The angular deflection θ of the boom of a horizontal pendulum induced by an earth tilt of ψ radians is such that $\psi = i\theta$, where i equals the angle between the line connecting the upper and lower supports and the vertical. From the pendulum formula it may be shown that

$$\psi = \frac{4\pi^2 l}{gT_0^2} \times \frac{ds}{Ar} ,$$

where l = distance from axis of rotation to center of oscillation, T = period of pendulum, d = displacement of writing pen due to the tilt of ψ radians, s = short arm of magnifying lever, r = long arm of magnifying lever, and A = total length of pendulum boom. Let the displacement d equal 1 centimeter; and, substituting the constants of the Bosch-Omori instruments of the Hawaiian Volcano Observatory, we have, after multiplying the right-hand member of the equation by 206,265 so that the result will be in seconds,

$$\psi = \frac{4\ \pi^2 \times 25}{978.236 \times 7.7^2} \times \frac{1 \times 0.86 \times 206{,}265}{102 \times 24.5} = 1.21 .$$

Then a deflection of 1 centimeter of the writing point corresponds to a ground tilt of 1.21 seconds.

Every time there is a change in ground tilt, there is a change in pendulum period and a change of tilt sensitivity, varying as the square of the period, so that the value determined applies only when the period of the pendulum has been maintained. This has been kept very near 7.7 seconds since 1918. The Bosch-Omori seismograph at the observatory, with a static magnification of about 115 and a period of 7.7 seconds, is sensitive enough to record a depression of 1

centimeter in 16 kilometers or 0.4 inch in 10 miles. One second of arc is equivalent to 0.272-inch depression or elevation at a distance of 1 mile. Charts derived from measurements of tilt changes recorded by the Bosch-Omori seismograph at the observatory are the only ones discussed in this article.

GRAPHICAL REPRESENTATION OF TILT

In 1927 R. M. Wilson[4] plotted the resultant values for that year. Dr. H. A. Powers plotted the data by this method for several years but left the observatory before publishing the results. In this paper resultant plotting is given from the time of establishment of seismograph records in 1913 to April, 1941.

To aid in visualizing the ground tilt, results of the daily readings are plotted on co-ordinate paper lined ten to the inch. One-millimeter change on the seismograph is plotted to $\frac{1}{10}$ inch, so that 1 inch on the paper is equal to 1.21 seconds of arc. An arbitrary numerical value was assigned to the starting-point, and all tilt has been plotted on this base since. The east-west migrations of the seismograph pen are plotted as abscissas and the north-south as the ordinates. During the twenty-seven years of measurement, it has been found that tilting movement on the northeastern rim of Kilauea crater, considered as the path of the top of a vertical rod, describes an annual loop of from 5 to 20 seconds of clockwise rotational arc with the loop elongated in a north-northeast to south-southwest direction, the greater axis usually having about twice the length of the shorter one. The average is about 12 seconds per year. During the development of the major clockwise loop many minor ones occur, which almost without exception progress in a counterclockwise direction. In general, tilt is northeasterly during the warmer summer and fall months and southwesterly during the cooler late winter and spring months. Jaggar and Finch[5] have shown that seasonal temperature changes and tilt at Kalauea are correlated; but loading due to rainfall is not related. A direct relation to lava eruption, confirming tilt changes, was shown by precise leveling by R. M. Wilson in 1921 and 1927.[6]

[4] *Bull. Hawaiian Volcano Obs.*, Vol. XV, No. 12 (December, 1927), p. 96.

[5] *Op. cit.*

[6] "Ground Surface Movements at Kilauea Volcano," *Univ. Hawaii Res. Pub., No. 10* (1935).

Lava movements apparently affect tilt directly. This is shown in irregularities of the annual curve and in accumulated tilt from year to year. Accumulated tilt may be thought of as relative average change of position or migration of the annual loop or as relative displacement at corresponding periods of successive years. Whenever considering tilt trends, the observatory staff always makes allowance for the seasonal loops.

Three types of tilt graphs are regularly plotted at the Hawaiian Volcano Observatory. One is simply a daily curve derived from lines connecting points plotted as described. This produces an irregular diagram rather confusing at times. In order to smooth the annual curve a system of overlapping 7-day mean is used for the second type. This makes any plotted point a 7-day average. As tilt moves the seismograph pens beyond normal registration range, they are realigned and proper corrections added to or subtracted from the last-measured tilt value, depending on direction of adjustment. The third system used separate graphs for north-south and east-west components. In this system the dates are the abscissas and the amount of tilt (in millimeters) the ordinates. Millimeter graph paper is used with the single divisions representing days and millimeters of tilt as measured on the seismograph record. The advantage of this type of graph is its convenience for comparison with other data.

The center of Halemaumau is S. 50° W., and the center of Kilauea crater is S. 40° W. from the observatory. The long axes of the annual loops average S. 30° W., which suggests that factors other than concentric tumescence around either Halemaumau or Kilauea influence the direction of tilt at the observatory. The factors may be topographic or structural. It seems likely that the area south of the observatory is made up of a series of fault blocks stepped downward on the southeast and southwest toward the sea. If this is true, there would be besides the southwesterly Kilauea rift, as indicated by the fractures in the southwesterly crater wall and dikes in Halemaumau, another rift running to the east through Kilauea Iki. Such a fault-block system might easily explain the relatively small east-west tilt on the northeast Kilauea crater rim, which would tip more to its north than to its east, directed by greatest ease of ground movement.

Figures 2–7 are copies of original plats which were made at the observatory. Figure 2 shows the Bosch-Omori, 7-day mean, tilt path for 1932. The year's loop is very irregular. Apparently during 1931 the lava-gas pressure under Kilauea crater had forced the tilt well to the north and east. This effect continued until December 23, when Halemaumau inflow began. As the eruption continued, pressure was released, resulting in the westerly and southerly tilt's lasting until January 18, 1932. After that an easterly tilt of 2 seconds of arc occurred, presumably because some pressure built up after the vent had sealed off. During the sealing period—probably January 4–18—irregularities occurred which may have been sympathetic to resulting pressure changes in the crater. The pressure release as a result of the eruption allowed considerable southerly tilt to occur. However, Figure 2 shows that the more easterly accumulated tilt of 1932 was a forerunner of the building-up of pressure under Mauna Loa preceding the eruption of the summit crater December 2–18, 1933, almost due west of the observatory. Simultaneously, Kilauea crater was no doubt adding to the increased easterly tilt.

In Figure 3 a southerly and easterly tilt began building up about October 29, 1933. A maximum was reached about November 26. On December 2 Mauna Loa erupted at the summit crater. Tilt showed sympathetic reactions between December 3 and December 24. The "jog" in the line (December 17) corresponds to the sealing-off and end of the eruption on December 18. Tilt continued west and north until December 24, when it changed to east and north, possibly because of increases of pressure under Kilauea resulting from termination of the Mauna Loa activity. It is of interest to note that 1933 tilt ended to the north and west of its starting-point, indicating that tilt had accumulated to the north from Kilauea pressure and probably had altered to the west as a result of pressure release from Mauna Loa.

Figure 4 for 1934 continues the 1933 chart. Starting with January 7, the general progress of the annual loop was to the south and west in normal fashion. The interesting point, however, is that the southwesterly tilt ceased about $5\frac{1}{2}$ seconds from the low of 1933 and moved steadily north until August 5, when irregularities began to occur. Halemaumau began erupting on September 6. Tilting to the south-

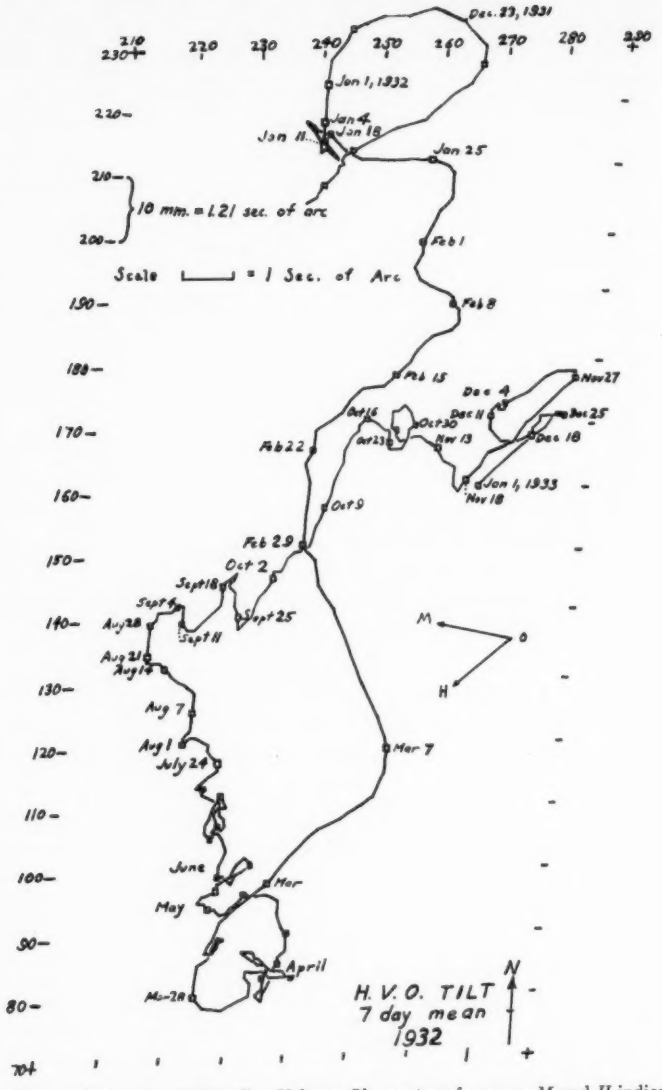

FIG. 2.—Tilt curve at Hawaiian Volcano Observatory for 1932. *M* and *H* indicate the direction of Mokuaweoweo and Halemaumau, respectively, from the observatory. The graph is slightly askew because the two seismograph pendulums were not oriented true north-south and east-west.

west followed until September 9, when recovery started and the normal trend continued in a northeasterly direction until January 6, 1935. At that time the ground on the northeastern rim of Kilauea

FIG. 3.—Tilt curve for 1933 at Hawaiian Volcano Observatory

had tilted approximately 3 seconds of arc northeast of its position at the same date in the preceding two years. In other words, in 1933 and 1934 tilt had accumulated to the north and east.

Figure 5 (1935) continues from the preceding chart and marks the last tilt-eruption curve. This curve is highly irregular. In June some 2 seconds of arc had again accumulated to the northeast over a

similar period in the preceding year. On October 6, southeasterly tilt began, continuing until November 17, when Mauna Loa summit crater and northeasterly rift began an eruption which continued until January 2, 1936. The tilt recovered most of its northerly trend,

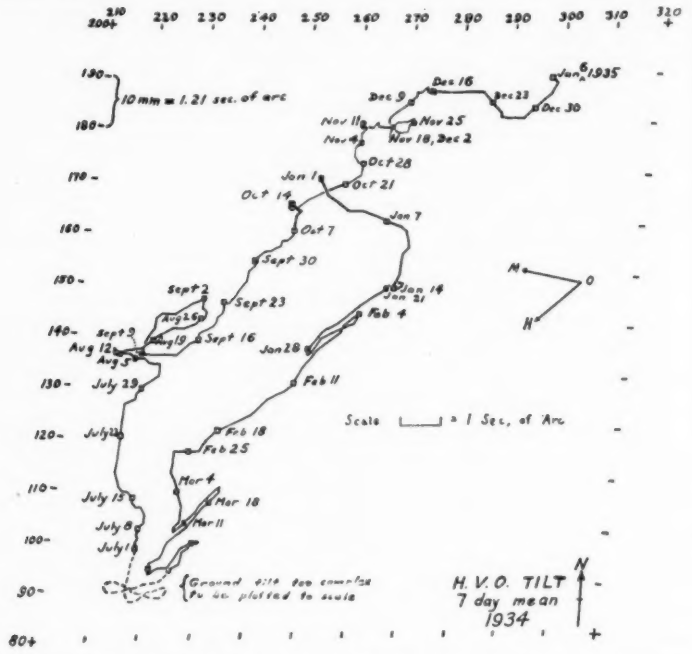

FIG. 4.—Tilt curve at Hawaiian Volcano Observatory for 1934. Note the irregularities in August and September occasioned by the outbreak of Halemaumau starting on September 6.

which would be normal for Kilauea, and then moved rapidly to the west, December 22–29, during the decline of the Mauna Loa eruption. It is striking that northerly tilt did not recover as it had done in preceding years. Possibly sympathetic pressure under Kilauea had been reduced with the Mauna Loa eruption.

Figure 6 shows relations which followed. Northeast tilt continued to accumulate in 1936. In 1937 and 1938 there was a steady recession to the southwest. During the last six months of 1939, however,

northerly tilt again predominated. By December, 1939, northerly tilt had recovered beyond that of the same period in 1937, although easterly tilt had not so recovered. The dotted line marking mean annual tilt indicates a definite recovery corresponding roughly with

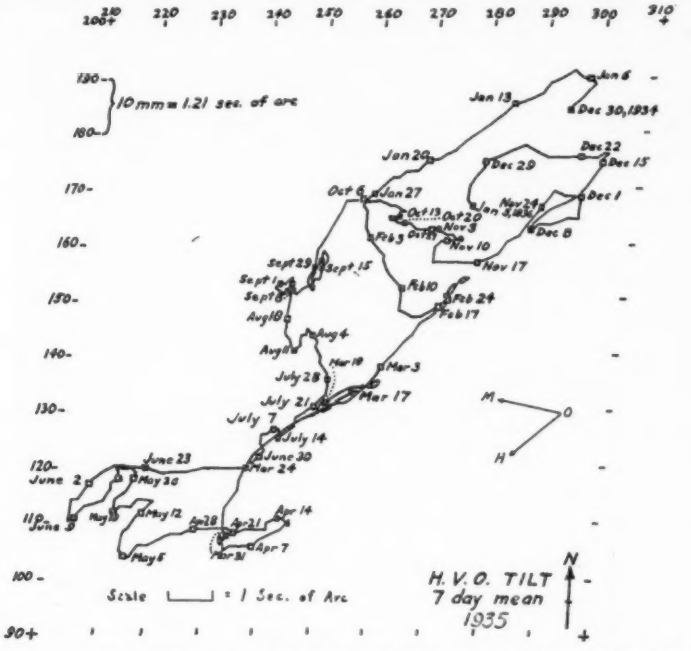

FIG. 5.—Tilt curve for 1935. Note the unusual southeasterly tilt starting October 5 that led up to the summit outbreak of Mauna Loa on November 17.

the peaks. Furthermore, the plotted 7-day mean loops of 1937, 1938, and 1939 were open and relatively regular. In all the smoothed curves dates of tilt changes do not always correspond exactly to visible or other volcanic changes, as they are affected by possible sudden changes before or after the date concerned which are not clearly shown because of the smoothing by overlapping means.

The most interesting chart of the entire group is Figure 7, which gives a general picture of tilt changes at the northeastern rim of Kilauea crater from 1913 to the end of 1940. In this case average

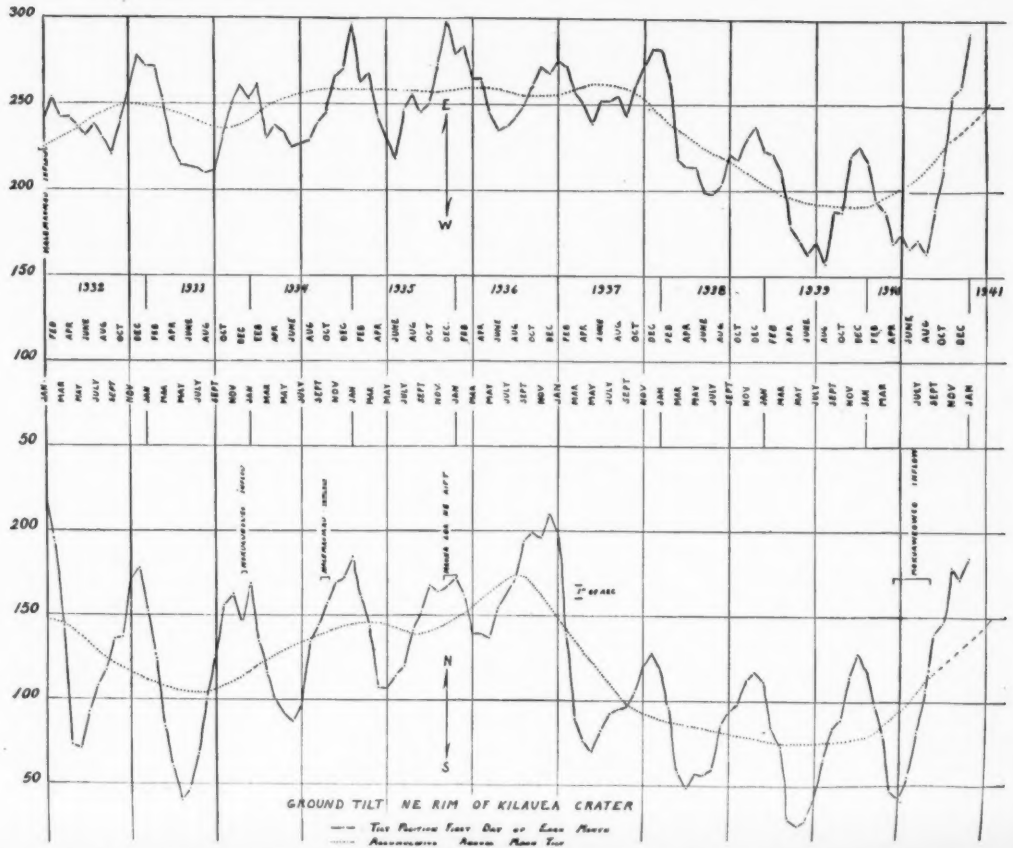

FIG. 6.—East-west and north-south tilt, 1932–40, plotted separately. The values are seven-day overlapping means

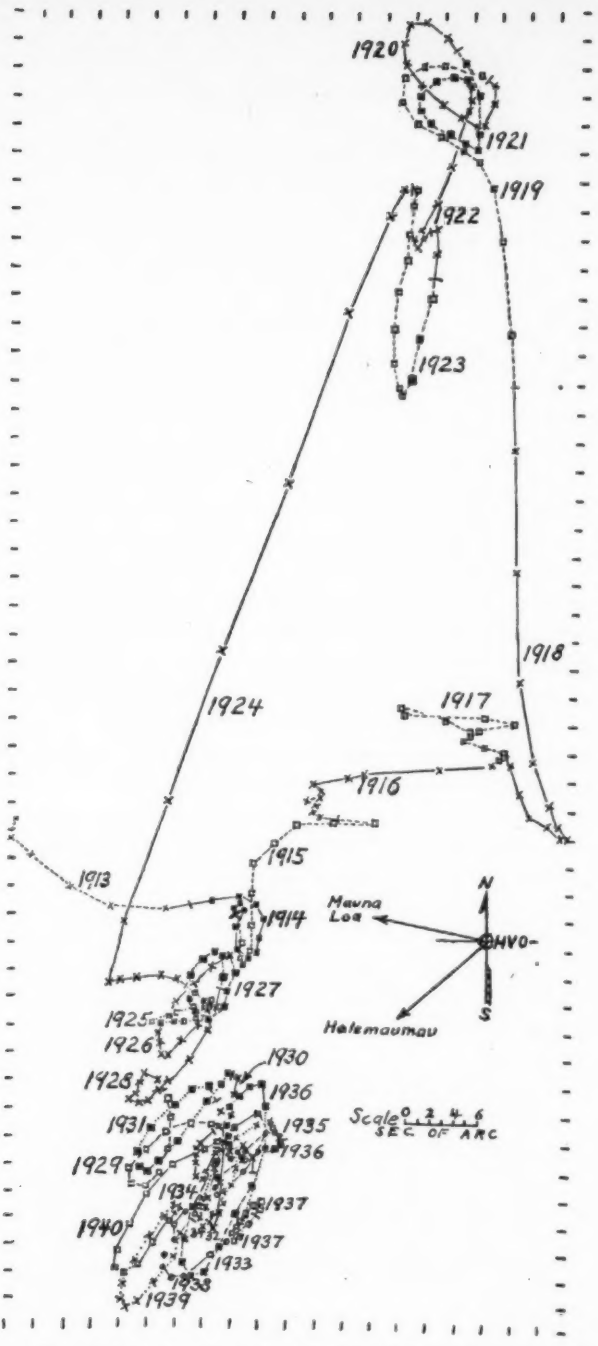

FIG. 7.—General chart of resultant tilt at Hawaiian Volcano Observatory, 1913–40, starting from an arbitrary zero. Tilting to the north and east indicates tumescing, to the south and west subsidence.

monthly tilt has been determined and these values plotted as overlapping means in groups of five in the same manner that the daily Bosch-Omori tilt was plotted by 7-day means. The relative position of each month is represented by a square, and in order to simplify the resulting maze each yearly trace is given a different design. During a portion of each of two years, 1916 and 1917, tilt records were not obtained because of instrumental difficulties. That period is indicated by a dotted line using an *X* for each month rather than a square. The major loop progresses counterclockwise, but all others are of normal clockwise movement. That part of the plat from 1913 to 1931 inclusive was worked up and plotted by predecessors of the author, the remainder by the author.

Changes in ground tilt represented by Figure 7 bear a direct relation to volcanic activity during the same period. There was strong easterly tilt from July, 1913, to July, 1918, with only slight westerly recession in 1919. Mauna Loa summit crater erupted in 1914; the southwesterly rift was active in 1916, and in 1919 it produced the Alika flow. The flows were progressively bigger. From March to August, 1919, there was considerable westerly tilt. This continued until August, 1924, when marked easterly tilt developed. In 1926 the Hoopuloa flow from the southwesterly rift of Mauna Loa occurred. In 1928 and 1929 there was recession to the west again, but recovery to the east was resumed in 1930 and continued until 1936. During that period there occurred the Mauna Loa summit eruption of 1933 and the northeasterly rift eruption of 1935–36. Westward tilt followed in 1937, 1938, and 1939. The relative east-west position at the beginning of 1941 is about the same as that for the years 1914 and 1926 with Mauna Loa eruptions. Tilt position indicates that there has been no marked decrease in the internal-pressure conditions of Mauna Loa and that its eruptive possibilities are equal to 1913 or 1925, for instance.

The proximity of Kilauea makes its effects on the observatory tilt more striking. It should and apparently does affect the northeastern crater-rim tilt more in the north-south than in the east-west direction. In 1913, 1914, 1915, 1916, and 1917 there was pronounced annual autumn tilt. Lava rose simultaneously in Halemaumau, and this in turn was apparently sympathetic to increases of pressure under Mauna Loa. Beginning in 1918, the Mauna Loa influence is

masked by the great changes taking place within the Kilauea dome reflected by rising lava in Halemaumau and 53 seconds of northerly tilt between May and January of that year. Strong northerly tilt continued until August, 1919, culminating simultaneously with Halemaumau lava overflow. In 1920 outflows occurred in the Kau Desert, and Halemaumau overflows occurred again in 1921. Following this there was lava recession with outflow in the vicinity of Makaopuhi during 1922 and 1923. Southerly tilt was marked during those two years. However, in the fall of 1923 there was recovery of northerly tilt with an accompanying rise of lava in Halemaumau. This was followed by strong southerly tilt of 81 seconds between January and July, 1924. In May, 1924, lava in Halemaumau receded to an unknown depth, and activity reached a culmination during that month by steam-blast explosions and the collapse of Halemaumau and to some extent the entire dome of Kilauea. After this, Kilauea crater was active only periodically with Halemaumau inflows, which occurred in July, 1924; July, 1927; January, 1928; February and July, 1929; November-December, 1920; December-January, 1931–32; and September-October, 1934. Southerly accumulative tilt continued during 1925 and 1926 but recovered in 1927 to the north. Southerly tilt again occurred for 1928 and 1929 with little change during 1930–31. Slight southerly tilt accumulated during 1932–33 and then recovered in 1934 to a point north of the two preceding years. Halemaumau inflow of September, 1934, was the last extensive Kilauea activity to date. Northerly tilt continued during 1935 and 1936. During 1937, 1938, and 1939 southerly tilt steadily accumulated; and, with the exception of the Chain-of-Craters seismic crisis of May and July, 1938, Kilauea has had its quietest period of the current cycle of events. However, 1939 ended with accumulated tilt again to the north; and the first three months of 1941 have borne out the suggestion that a new cycle of northerly tilt may have started and with it the possibility of a coming increase in volcanic activity in the Hawaiian system of eruptive vents.

TILT AND LEVEL CHANGES

R. M. Wilson's leveling work has confirmed the major changes described. Precise levels were run up from Hilo to Kilauea in 1912, 1921, and 1927. These showed that apparently between 1912 and

1921 the Volcano House bench mark was elevated about 2 feet, and between 1921 and 1927 it was lowered 3.5 feet. Comparison with Figure 7 shows that the values coincide with tilt changes in both time and relative amounts. As would be expected, the greatest change was around Halemaumau, where the collapse accompanying the 1924 explosive eruption was greatest. There were no tilt records available that close to Halemaumau. However, tilt to the south was as great as 53 seconds of arc at the observatory. Later tilt records at the southeastern, northern, and western rims of Halemaumau do not follow and are of less magnitude than those of corresponding time at the observatory. This may be explained by the assumption that the "dome" of Kilauea is highly irregular, as shown by the contours of level changes by Wilson, and is probably made of a mosaic of blocks which may be highly differential in their movements. These two points are confirmed by irregularity of horizontal angle across the crater floor and by inconsistent changes within local crater-level nets. Another factor that would produce an apparent inconsistency between tilt at Halemaumau and at the northeastern rim of Kilauea is that the stations at Halemaumau are located nearly on top of the dome and could have a very large vertical component of movement and yet be little affected by the tilt shown by other stations on the slopes of the dome. It is likely that the magnitude of tilt, as was true of level changes, would decrease toward sea-level. It seems that the tilt probably is controlled more by local fault structures than by the dome, although both have their effects and operate simultaneously. Tilt instruments placed near the southwesterly rift should clarify this question, as there the greatest tilt, if controlled by local faults, should be in a northwest-southeast direction or almost at right angles to that at the observatory.

The actual value of the level changes as determined by Mr. Wilson may be greater than the computed changes. The final values were made as low as possible by the application of corrections for all possible sources of error. The rod length varied with the humidity; and corrections for humidity, which varied from day to day and hour to hour, were most troublesome. To eliminate the possibility that apparent level changes are due to rod errors, values approximating the maximum humidity corrections were used.

A local level line from the Spit bench mark on the south rim of Kilauea crater to the northwestern Halemaumau bench mark has shown great relative change since 1934. Between October 17, 1934, and January 17, 1941, the northwest station lowered 1.854 feet relative to Spit. Halemaumau western tilt station has shown, during the same period, almost continuous northwesterly tilt showing agreement and suggesting a block movement in that direction. If it is assumed that the Spit has remained more or less stationary, then the crater floor of Kilauea has settled, and accumulated tilt should be to the south. All other evidence confirms this condition.

Between 1921 and 1924 southwesterly tilt at the observatory was about 53 seconds of arc, and relative level changes between the Spit and North Pit stations were 3.371 feet. Between 1924 and 1940 there was a southerly tilt of about 14 seconds of arc; we know that during the same period the relative change of level between Spit and N.W. Pit was at least 1.5 feet. Tilt and level changes here again seem to be proportional. To speculate on this, one may perhaps assume that the Volcano Observatory has settled about 1 foot relative to sea-level since 1927.

EFFECTS OF LOCAL LOADING ON TILT

In a previous paragraph it was stated that rainfall and tilt had been found not correlated. In *Volcano Letter No. 303, October 16, 1930*, there is a discussion indicating a correlation of tilt and rainfall about as follows: After the deposition of the ash of the 1924 explosive eruption of Kilauea, it was noted that after heavy rainfalls the crater floor was dotted with numerous pools of water which lasted for several hours after the rain. The Halemaumau seismograph building is located 30 feet north of one of these pool basins, which holds about 4,000 pounds of water. This means that a hard rain adds about 4,000 pounds of load to the surface of the ground just south of the seismograph. Five fillings of this basin were carefully timed, and each occasion was accompanied by abnormal southerly tilt.

The author also has noticed indications of tilt as reported above. Mr. Finch questioned the effectiveness of the weight of the ponded water in producing the observed tilt and suggested that a practical

test be made by artificial loading of the pool basin under consideration. Consequently, on the afternoon of January 30, 1941, two automobiles, total weight 7,000 pounds, were placed in the basin. There was no apparent change of any kind on the pit seismograph over a period of about 1 hour. As a further check the automobiles were then placed side by side with their front bumpers almost touching the seismograph building, and still no tilt effect was discernible. This appears conclusively to answer the question; and rainfall "loading," at least in pools, does not affect the seismograph. It is possible that greater loading of a large area to the south of the pit seismograph could do this, but it seems more likely that the change may be caused by temperature changes accompanying heavy rains. It is also of interest that the amount of tilt varies greatly on the different occasions and that it seems roughly proportional to the duration of the storm in hours. But was the amount of water involved the same in each case?

As further confirmation of the small effect of local loading, a series of events during the past few months (October, 1940—March, 1941) near the Volcano Observatory have been of interest. The site of the Volcano Observatory has been chosen for the location of a new hotel. During the fall months the old shop, garage, a residence, and a large part of the observatory were torn down and a large amount of earth fill made to the southeast of the Bosch-Omori seismograph. A little later an excavation was made to the northeast of the instruments, and steam vents heretofore sealed were opened to the air for several weeks. Tilt for the most part was not in agreement with the loading and unloading. The temperature of the seismograph cellar was lowered during part of the work and stayed down for several months. In general the abnormal behavior of tilt did not directly correspond to the temperature change. Daily for several weeks a road roller, weighing about 6 tons, was parked about 5 feet south of the seismograph cellar, where it stayed for about 15 hours each day. No evidence of its presence was detected on the seismograph. From the foregoing remarks it is natural to conclude that the tilt actually is caused by more profound disturbances and probably is one of the better keys to volcanic behavior.

PREDICTION OF VOLCANIC ACTIVITY

Early in 1940 it became obvious that the accumulated tilt was much farther northeast than in the preceding year. Coming volcanic changes were suspected, and these suspicions were confirmed by the Mauna Loa eruption, beginning April 7, 1940. Volcanic pressures had tilted the ground farther east and north than it had been for 2 years. Dr. Jaggar was influenced in his public prediction of an imminent eruption in March, 1940, by the behavior of the tilt, as well as by earthquakes on the Mauna Loa seismograph. Inspection of Figure 6 will show that the tilt has continued to accumulate to the north and the east. As previously stated, current tilt behavior has been extremely erratic during the past few months; and during the early months of 1941, when tilt should be going rapidly to the southwest, it has been relatively static or suspended with loops but with no progression taking place. Because of this condition, coupled with the extreme seismic quiet also current, observation of Kilauea and Mauna Loa behavior cannot be too close.

With continued accumulation of tilt data, more light is certain to be thrown on prediction of volcanic activity. From the facts here illustrated and discussed it seems obvious that ground tilt is an extremely important factor in volcano studies. More instruments should be developed. Dr. Willard H. Eller of the University of Hawaii physics department, in co-operation with the Volcano Observatory, is working on the problem, and several new instruments have been developed which are promising. The need is for a self-recording "tiltmeter" little affected by temperature, which will give a clear picture of ground movement in any direction. Such instruments well placed and in sufficient numbers would not only be useful in determining changes in lava movements but would also be of help in clarifying the complicated structural relations of the Hawaiian volcanoes.

ACKNOWLEDGMENTS.—In acknowledgment the author wishes to thank Mr. P. E. Schulz, of the Hawaiian Volcano Observatory, for tracings made of charts Nos. 1, 3, 4, and 6 and used for reproductions here illustrated. The many helpful suggestions by Mr. R. H. Finch were greatly appreciated.

SAND STALAGMITES

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ABSTRACT

Sand stalagmites composed of shell and quartz sand and having an origin analogous to that of ordinary stalagmites occur in a limestone cave on the southern coast of western Victoria. They have grown beneath dripping, hollow stalactites, where calcareous solutions seeping down through the underlying sand have gradually cemented portions of the sandy floor of the cave into grotesque shapes. Small drip mounds surround drip craters at the summits of most of the sand stalagmites, and ledgelike structures on the forms result from the cementation of different surface levels of the sand on the cave floor. Accretions to the sandy floor result principally from wind-blown sand being periodically carried into the cave.

INTRODUCTION

Curious structures formed from the cementation by secondary calcium carbonate of portions of beach sands on the floor of a limestone cave have been discovered in Loch Ard Gorge (Fig. 1), 4 miles east of Port Campbell on the southern coast of western Victoria. The rocks of the district are calcareous clays and limestones of Miocene age, capped by thin deposits of post-Miocene clays.

The structures are called "sand stalagmites" because they are composed mainly of shell and quartz sand, and their mode of formation is somewhat analogous to that of stalagmites. No descriptions or records of identical structures are known to the author.

MODE OF OCCURRENCE

The sand stalagmites are found buried in loose sand comprising the floor of Carmichael's Cave and are situated beneath hollow stalactites (Fig. 2) which drip at varying rates—usually one drop each minute or two—from heights of a few feet above the cave floor.[1]

The sand stalagmites, which are not numerous, are confined to the southern side of the cave where the roof is relatively low and the sand consequently undisturbed by visitors. The sea enters a short distance into the cave at high tide, and the sand stalagmites are

[1] In Fig. 2 the size of the sand stalagmites is greatly exaggerated, compared to the size of the cave.

formed only above high-tide mark. The sandy floor of the cave slopes gently upward from the mouth to the back.

Although stalactites are numerous in a near-by cave (Pearce's Cave) at the head of the eastern arm of Loch Ard Gorge (Fig. 1), sand stalagmites are absent, because the floor here consists of rock and mud and, in addition, is swept by flood waters discharging from a sinkhole through the cave to the sea. In Carmichael's Cave, on the

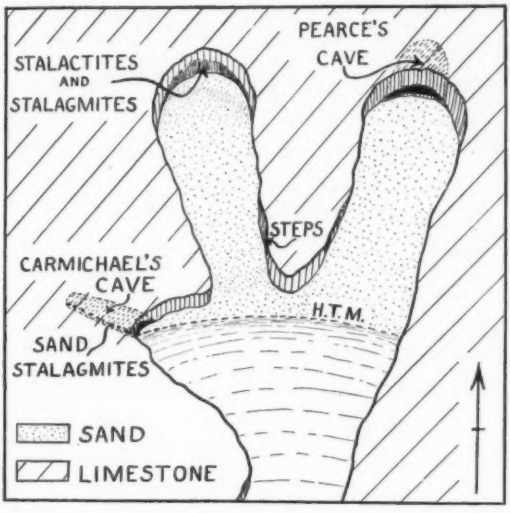

FIG. 1.—Sketch map of Loch Ard Gorge showing position of Carmichael's Cave containing sand stalagmites.

other hand, calcareous solutions descending from the surface through 100–150 feet of limestone seep gradually along joint and bedding planes and build innumerable thin-walled tubular stalactites on the roof of the cave, seldom more than 3 inches long and $\frac{1}{4}$ inch in diameter. Where calcareous solutions from the hollow stalactites drip upon the sand occupying undisturbed positions on the cave floor, secondary carbonate is deposited, and the sand grains become cemented together into the sand-stalagmite formations. Where the solutions drip upon exposed parts of fallen limestone blocks, carbonate deposits form small stalagmites and stalagmitic encrustations (Fig. 2).

COMPOSITION

The sand of the cave floor in which the sand stalagmites are formed is similar in composition to that forming the beach and the sand ridges at the head of Loch Ard Gorge. The sands are composed of 30 per cent insoluble matter, mainly quartz grains, and 70 per cent acid-soluble matter, mainly shell fragments, some of Recent species, others of Tertiary forms from the fossiliferous Miocene rocks which form the high vertical cliffs of the neighboring coastline.

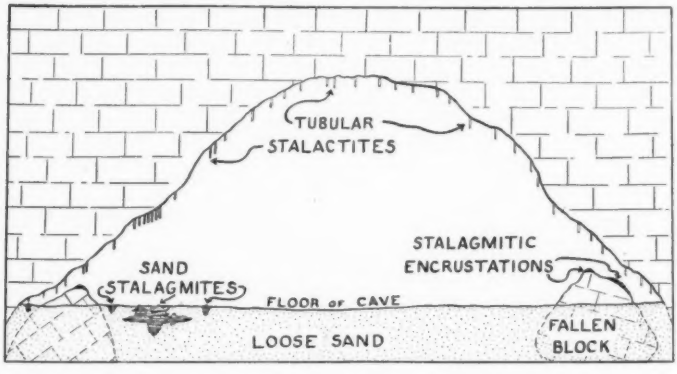

FIG. 2.—Sketch section through Carmichael's Cave showing position of sand stalagmites buried up to the drip mounds in loose sand.

In the sand-stalagmite structures the amount of secondary calcium carbonate added by solutions dripping from stalactites is about 13 per cent, since 83 per cent of a portion of the large compound sand stalagmite illustrated in Figure 3 was acid soluble. The portion of the sand stalagmite employed in the solubility test included a drip mound, a small sand bowl, and a portion of a ledge formation.

SIZE AND SHAPE OF STRUCTURES

The sand stalagmites assume grotesque forms, as indicated in Figures 3 and 4. The smallest example seen was 1 inch across and $1\frac{1}{2}$ inches deep (Fig. 4, No. 5), while the largest, a compound form like that in Figure 3, was nearly 3 feet across the top and between $1\frac{1}{2}$–2 feet deep.

The bases of some of these forms are flat (Fig. 4, No. 1), but most

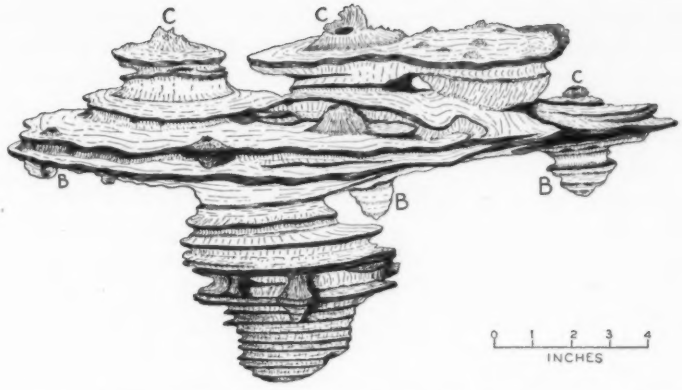

FIG. 3.—Compound sand stalagmite showing terraced arrangement of ledges and bulbous base. *B*, sand bowls, and *C*, drip craters.

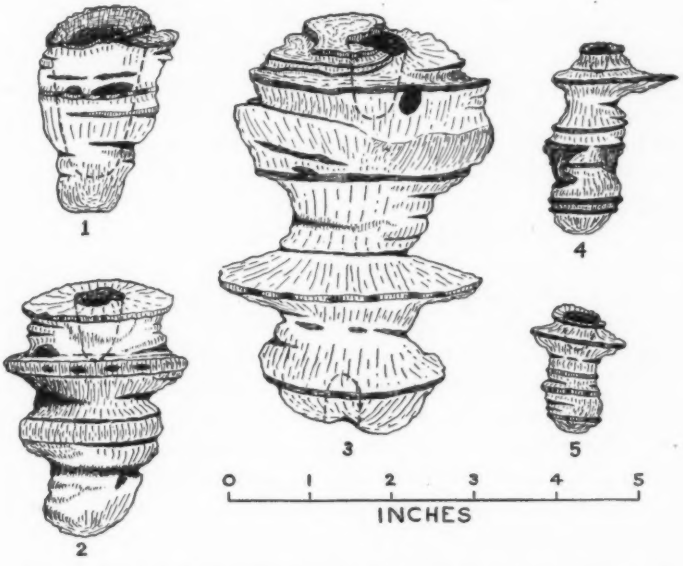

FIG. 4.—Single sand stalagmites from floor of Carmichael's Cave. Heavy broken lines indicate depths and widths of drip craters.

are rounded (Fig. 4, Nos. 2, 4, and 5). Many are surmounted by small mounds, each of which surrounds a small crater varying in diameter in different forms from $\frac{1}{4}$ to $\frac{3}{4}$ inch. Other forms are open at the top and cup-shaped (Fig. 4, No. 1), with the aperture up to $1\frac{1}{4}$ inches across.

The craters are initiated as drip marks, around which a mound is gradually formed by processes of cementation, and are kept free of loose sand grains by the splash of calcareous solutions falling a distance of several feet from the roof of the cave. In some instances the crater holes are continued right through the sand stalagmites as hollow cylinders, because the downward soakage of the calcareous solutions is more rapid and more sustained than lateral spread, so that ledge structures are not prominently developed. In such examples the stronger downward flow of the solutions is due to the greater strength and rapidity of supply from the stalactites overhead, and so no pronounced drip mounds with impervious retaining walls are formed. In many of the sand stalagmites the drip craters are shallow (see broken lines in Fig. 4), and the portions below them are composed of less firmly bound sand than that in the bulk of the structures.

The constituents of the sand stalagmites are not particularly well cemented together when first collected, as the forms are then still wet. On drying out, however, the structures become more compact, although even then many sand grains fall away on handling. The mounds surrounding the drip craters, however, are hard and compact in most forms, since secondary calcareous material is more concentrated in them, and sand grains are fewer. These drip mounds, situated on the upper portions of the sand stalagmites, are exposed just above the level of the sand on the cave floor, while the top, ledgelike structures (see Fig. 4, Nos. 2, 4, and 5) are covered over with a sprinkling of loose sand grains. The ledges are formed by the splashing-out and spilling-over of calcareous solutions from the drip craters on to the surrounding sand grains, which in time become cemented into ledgelike girdles around the drip mounds. Some of the ledges are cellular in appearance around their peripheries, as indicated by the dark areas in the second ledge from the top of the

form shown in Figure 4, No. 2; this feature is apparently a result of irregular cementation in parts of the outer limits of the structures.

Beneath clusters of hollow, dripping stalactites, the sand of the cave floor becomes cemented into terraced, compound forms with prominent ledges, as in Figure 3. The number, thickness, and lateral extent of the ledges are determined by the frequency of changes in sand level on the cave floor and local differences in the rate of supply and evaporation of the calcareous solutions. Small sand bowls (*B*, Fig. 3), dependent from beneath some of the ledges, are situated immediately below drip craters (*C*, Fig. 3). The bulbous base of the structure is formed underneath the most continuously dripping stalactites of the cluster. The presence of drip mounds on ledge structures situated some distance below the top level of the compound sand stalagmites indicates that for such examples, which were covered over by 2 or 3 inches of loose sand, the supplying stalactite had ceased to drip.

REVIEWS

Sarkî Anadolu ve Mücavir Mintakalarin Tektonik Ana Hatlari: Tektonische Grundzüge Ostanatoliens und benachbarter Gebiete. By P. ARNI. ("Contributions of Turkish Institute of Stratigraphic Research," Ser. B, No. 4.) Ankara, 1939. Pp. 90; figs. 7; pls. 5.

This treatment of the tectonics of eastern Anatolia, presented first in Turkish and then in German, will introduce many geologists to a region with which they are relatively unfamiliar. In general one may note various similarities with Alpine geology, although strongly drawn-out recumbent folds are much less in evidence in Anatolia. Instead, broad belts of imbricate structure, with much slice faulting and some overthrusting, are the most characteristic structural features. The areal arrangement of these zones together with their opposing directions of surficial movement is very well portrayed on a large map which gives the generalized tectonic features from the Sea of Marmora to Afghanistan. From south to north the mapped units are (1) Anatolian-Iranian border chains, (2) Iranides, (3) Taurides, (4) Anatolides, and (5) Pontides, or northern border chains.

In the main, the border chains exhibit surficial thrust movement directed outward from the orogenic complex. The inner zones show less constancy of yielding; various individual units within them are noticeably wedgelike in shape with inward-dipping thrust faults on each side. The Cretaceous geosynclinal segments of the Iranides and the Anatolides were strongly intruded by greenstones. It is of particular interest to note that the Anatolian-Iranian (southern) folded border chains curve through an arc of 90° in southeastern Anatolia and, in the opinion of the author, continue south-southwest in the rift system of northwestern Syria.

R. T. C.

The Pleistocene Gravels of Iowa. By GEORGE F. KAY and PAUL T. MILLER. Des Moines: Iowa Geological Survey, 1941. Pp. 232; figs. 61.

This is a comprehensive geological study of the gravels of Iowa. It presents the subject from the point of view of the Pleistocene stratigraphic history and origin of the deposits. The report is based on the twenty-five

years of intensive study of the state's glacial deposits by the senior author supplemented by sedimentological field and laboratory studies by the junior author.

After a brief chapter summarizing the Pleistocene history of Iowa and another on the past and present interpretations of the gravel deposits, the occurrences are presented chronologically: Nebraskan, Kansan, Illinoian, Loveland, Iowan, and Mankato. Subdivision into upland gravel and terrace gravel adds clarity to the descriptions. Terrace gravels of glacial outwash were formed during Iowan and Mankato time and interglacial terrace gravels during Loveland time by the erosion of Kansan drift.

The gravels are of various origins: frontal kames, outwash plains and valley trains, kame terraces, and several types of gravel masses incorporated in till. The results of the expert laboratory study, while useful to the engineer, failed to reveal any basis for differentiating age or origin of the gravel. The volume is very well printed and is well illustrated with maps, photographs, and tables. It will become one of the important working tools of the Pleistocene geologist as well as a significant contribution to the economic geology of Iowa.

PAUL MACCLINTOCK

Soil Physics. By L. D. BAVER. New York: John Wiley & Sons, Inc., 1940. Pp. xi+370; figs. 70; pls. 4. $4.00.

Soil physics is a branch of soil science which concerns itself with the physical properties of the soil. During the last two decades this branch of knowledge has grown rapidly, but books which draw together the principles of the subject for classroom use are relatively few. The author has performed an important task in making available these principles for presentation at an advanced undergraduate or graduate level. The reviewer would also like to call the attention of geologists to the volume because of its concise presentation of a field not wholly remote from geology.

After a brief historical Introduction, the author considers the mechanical composition of the soil. The treatment is well balanced and includes a discussion of the principles underlying both the dispersion of the sample and the size analysis itself. This chapter will prove helpful to geologists in the mechanical analysis of sediments. The next three chapters consider the physical properties of soil colloids, soil consistency, and soil structure. Throughout the discussion the author develops his principles from experimental data. He does not hesitate to introduce quantitative concepts where they are helpful, and in general the mathematical

treatment is kept at a suitably elementary level. The topics of soil water, soil air, and soil temperature follow. In connection with the movement of soil water, the author follows Buckingham's concept of capillary potential. The driving force is visualized as the difference in attraction between two portions of the soil not equally moist. The mathematical detail here is greater than elsewhere, inasmuch as the principles are developed with partial differentials. At this level of presentation it would perhaps have been advantageous to introduce a more general potential function and to derive special cases from it.

The last two chapters of the book consider the relations between physical properties of the soil and tillage, runoff, and erosion. The last chapter especially, on runoff and erosion, should prove of interest to geologists for its analysis of the problem. Erosion is considered as a function of climate, topography, vegetation, soils, and the human factor. The several variables are discussed in the light of observational data, such as the effect of the degree of slope on erosion, the effect of vegetation on the amount of runoff, the infiltration capacities of various soils, etc.

The book as a whole is well illustrated with line drawings, mostly graphs showing experimental data. The author discusses his topics in adequate detail so that in many respects the book is wholly self-contained. Selected references are given at the end of each chapter as a guide for more detailed study of the topics.

W. C. KRUMBEIN

Handbook of Physical Constants. Edited by FRANCIS BIRCH, J. F. SCHAIRER, and H. CECIL SPICER. New York: Geological Society of America, 1942. Special Paper No. 36. Pp. 325; figs. 11. $1.40.

Attention should be called to this assemblage of the physical constants which are particularly useful to geologists. The volume contains twenty-one sections prepared by nineteen specialists co-operating through the Divisions of Chemistry, Physics, and Geology of the National Research Council. Most of the sections begin with a concise introductory text which effectively supplements the many tables of valuable data which follow. The edition has been made large enough to meet the needs of research men in geology, physics, and chemistry. Copies may be obtained on application to The Geological Society of America, 419 West One Hundred and Seventeenth Street, New York.

R. T. C.

Outline of the Geological History of Spitsbergen. By ANDERS K. ORVIN. Translated by GUNNAR HORN. Oslo: Skrifter om Svalbard og Ishavet, Nr. 78, 1940. Pp. 57; pls. 3; figs. 12.

A brief review of the geological history of Spitsbergen, with special reference to the tectonics, is given in this paper. In Spitsbergen all pre-Downtonian sedimentary rocks are known collectively as the "Hecla Hoek formation," which comprises strata ranging from pre-Cambrian to middle Ordovician. These were strongly folded and overthrust during the Caledonian mountain building, when igneous masses were also intruded. The igneous rocks of this time are chiefly a gray, strongly foliated granite, and a red, younger, nonfoliated granite. The first is thought to be para-granite resulting from the remelting of Hecla Hoek rocks under hydrostatic pressure after termination of the Caledonian folding, and in the north it is possible to follow the Hecla Hoek into para-gneisses and these into granites.

Five geologic maps showing Spitsbergen as it was at various stages from the beginning of the Culm to early Tertiary are very helpful in portraying the historical development of these islands. The different rock systems are clearly and concisely described with emphasis on the features of especial significance in interpreting the sequence of events. Several episodes of the late Paleozoic Variscan deformation of Europe (Bretonian, Sudetic, Asturian, and probably Pfalzian) appear to be represented by prominent unconformities, some of which involved notable block faulting. There followed early in the Triassic an extensive prolonged submergence which, with some interruptions, persisted to Aptian time.

With the exception of the Caledonian folding, most of the pre-Tertiary earth movements were epeirogenic uplifts, some of which were accompanied by block faulting. In the Tertiary there was strong folding surpassed only by the Caledonian mountain building. To this and some later faulting the present aspect of Spitsbergen is largely due. Since sediments of the younger Tertiary are missing, it is impossible to fix the age of this Tertiary folding, but it was probably contemporaneous with the Miocene deformation of the Alps.

C. W. STERNBERG

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VADOSE AND PHREATIC FEATURES OF LIMESTONE CAVERNS

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ABSTRACT

Most living cave streams are misfits, engaged in altering ground plans or chamber cross sections, or both, better to suit their needs, and doing this by familiar procedures of surface streams. The chambers and ground plans undergoing alteration have been inherited from earlier, different, and now vanished conditions to which the caves were adjusted. The alterations are superimposed readjustments to the new conditions. The thesis of William Morris Davis that limestone caves are first and most largely developed below the water table is supported by observational data on cave ground patterns and on numerous features of cave floors, walls, and ceilings. Genetic classification of patterns and features is attempted with the purpose of establishing criteria for both phreatic and vadose origin. Nearly 50 per cent of the caves examined in this study possess traits from both experiences, very many have had only a phreatic history, very few are wholly vadose in origin.

In many caves an epoch of clay filling occurred after the phreatic solution ceased and before a lowering water table allowed the formation of free-surface streams. Some fills yet remain almost intact, others are fragmentary remnants, still others are recorded only by superimposed wall and ceiling modifications left by the streams which have removed the clay.

Most caves are out of adjustment with the topography of their region and therefore are older than the present cycle of erosion. Some caves beneath accepted peneplains seem to date back to the last stages of those earlier cycles.

A concept of concentrated subwater-table discharge, physically like the pressure flow in water mains, is argued from the character of the big springs of Missouri and from features of many cave chambers.

INTRODUCTION

Geologists interested in the origin and development of limestone caverns owe much to the masterly deductive argument for phreatic origin by William Morris Davis in 1930.[1] Professor Davis at the

[1] "Origin of Limestone Caverns," *Bull. Geol. Soc. Amer.*, Vol. XLI (1930), pp. 475–628.

time had "passed the age when underground exploration is advisable," and he pleaded with younger men to make the needed field investigations of cave forms and patterns which he discussed from a literature largely descriptive and lacking in critical genetic studies. From data which in large part were meager and indefinite, Davis elaborated a theoretical picture of ground-water circulation and phreatic solution of caves.

Stimulated, in part at least, by the Davis paper, several cave studies have since appeared, by Gardner, Malott, McGill, Moneymaker, Pohl, Stone, Rhoades and Sinacori, Swinnerton, Tullis and Gries, and the writer; some supporting, some denying Davis' thesis but none based on a really extensive acquaintance with caves. To know a large number of caves, to know what solutional changes water is producing in them today, to identify older cavity forms now being destroyed or altered in these caves—these are essentials in understanding how former conditions have differed from those of the present.[2]

Dripstone-free caves, considered as subterranean waterways, record many more details of the history of their water course and show much less alteration by accessory agents than do surface stream ways. Walls of such caves may be entirely the work of the subterranean waterway, whereas almost no surface valley's walls have escaped weathering, slopewash, and landslip. Ceilings of many such caves afford a very important record which no surface valley possesses.

Because cavern sculpture varies greatly in detail from cave to cave and because it is less familiar than that of surface valleys, recognition of repeating patterns of connected chambers and of definite forms of wall, ceiling, and floor has hardly begun, and interpretation has lagged still more. This study is an attempt at a genetic classification of shapes, forms, and patterns. Since conditions of subterranean flow are notably different below and above the water table and since this migrates downward as the erosional cycle progresses, valid criteria have been sought for determining what part of cave develop-

[2] Davis appreciated this when he wrote that "what is now most needed in the investigation of cavern origins is not so much a more detailed deduction of expectable features as a closer and more critical observation of actual features."

ment occurred before (Davis' first epoch), and what part after (his second epoch), the water table passed the cavernous horizon. Only after this lowering allows air to enter, can we study caves.[3] The cavern entered may be dry or it may have a free-surface stream on its floor, or an indubitable record of one, or it may lack all evidence that flowing water ever traversed it. The character of the record being made by existing free-surface streams will be considered under the first major heading of this paper.

Forms impossible for free-surface streams to have made will be considered under several headings. From their character and their relations to forms now being developed by existing cave-floor streams, some of these abandoned features will be ascribed to solution when below the water table. These are treated under the second major heading, "Phreatic Forms and Patterns."

The problem of determining the former existence and direction of current flow and whether it was free-surface or pressure flow is considered under an appropriate heading, as is also the evidence that solution in some caves occurred without water movement sufficiently vigorous to be styled a current.

Since many caves carry records of profound changes in the character of their former circulations, a section is devoted to five caverns exemplifying a sequence of events which has superposed later forms and patterns on earlier and very different ones.

Subterranean streams whose emergences constitute the large limestone springs of Missouri use completely water-filled cavern routes. Certain features of these streams are significant to cave theory and are treated under the heading, "Water-Table and Subwater-Table Streams."

Davis found difficulty in applying his theory of phreatic origin to caves in dipping beds. The writer believes he has solved that difficulty while holding to the same principles Davis advocated. This topic is treated under the heading, "Caves in Tilted Formations."

The Mammoth Cave region has yielded a wealth of information

[3] Geologists and engineers connected with the Tennessee Valley Authority have been able to hurdle this difficulty by means of the deep core borings and open-cut excavations for dam sites. See B. C. Moneymaker, "Subriver Solution Cavities in the Tennessee Valley," *Jour. Geol.*, Vol. XLIX (1941), pp. 74–86.

on various cave aspects other than forms and patterns. The genetic relations of the region's sinks to its caves bear directly on the problem of cave origin. Today's subterranean circulation has an important bearing on the problem. Caves on the downdip (west) side of Green River are believed to show one author's ideas of cave origin in error. Three sections are devoted to these three aspects of the Mammoth Cave region.

The writer is introducing the concept of an epoch of clay filling in normal cave history—an epoch between the earlier phreatic and the later vadose solutional epochs. Data for the concept occur throughout the paper in the descriptions of many caves. A summary of the concept is presented at what seems to be the logical place in the development of the writer's argument.

Carlsbad Cavern is one of several caves which never had the clay-filling experience, nor much, if any, later vadose solution. A section of this paper is given to the presentation of Carlsbad's history.

Davis believed that caves developed beneath peneplains—an idea virtually impossible under the theory of vadose origin. A section entitled "Cavern-making in the Erosion Cycle" contains what field evidence the writer has been able to collect on the question, with the tentative conclusion that Davis was probably right.

There is no nomenclature for erosional features of caves comparable to that for surface-valley features. In so far as one is attempted here, it will be as simple and as nearly self-defining as possible. Many of the forms can be explained only by their relations to others. Until the reader is familiar with a sufficient number of them, full genetic explanation will be deferred. Some topics, therefore, will be discussed two or three times in this paper, more ample treatment following the building of an adequate background.

Throughout this paper specific caves are cited and described as typifying particular features or combinations of features. The endeavor is to provide a larger factual basis for cave theory and to reduce the amount of assumption that characterizes some studies.

More than a hundred caves in fifteen states have been examined during this study, 80 per cent of them in flat-lying formations, 20 per cent in strata tilted at various angles up to vertical. The for-

mations involved range from Cambrian to Permian in age, the topography of the region from recent block uplifts to slightly dissected peneplains.

PRESENT-DAY STREAM WORK IN CAVES

Seven types of cave streams and cave stream work will be considered under this heading.

SMITTLE CAVE, MISSOURI, AND ITS STREAM

A splendid arch 25 feet high spans the mouth of Smittle Cave, its floor essentially at flood-plain level of the stream valley from which one enters. In unreduced dimensions, the cave extends back under the upland, a great railroad tunnel in proportions, for several hundred feet. A small stream (artificially ponded near the mouth) traverses the gravel-covered floor, only in flood time having the full width of the cave. Farther back, the walls of this great simple chamber possess deeply cut, horizontal, arc-shaped niches near the level of the detrital floor. There, remnants of a dense red-clay fill begin to appear above the gravel and into it the stream is now trenching. With increasing distance back, the surface of this clay fill gradually rises until it is scarcely 4 feet from the ceiling. The stream trench here has a meandering course, the meanders enlarging as deepening progresses so that small-scale slip-off slopes of clay descend from the flat top of the clay fill to the inside of meander loops. One sees exactly the same pattern in many surface valleys.

The significant feature of this cave stream's work, however, is meander undercutting into the limestone walls of the large simple chamber. For a chord length of a hundred feet, one meander is completely out of the big chamber, is back in a low crescentic niche cut in the limestone wall. On the inside of this curve (the side toward the main chamber) is a slip-off slope of limestone. Because deepening has occurred along with the meander enlargement, the niche is in effect a conical surface, nearly a half-cone. Since the stream hugs one side of its subterranean valley and its meander belt is hardly half the width of the clay-filled chamber, meanders in clay alternate with meanders in limestone. Limestone sills in the conical niches determine the rate of deepening and thus probably are responsible for

survival of the clay fill in the back end of the accessible part of the cavern.

A tributary chamber carrying a wet-weather stream enters the main a little downstream from the clay-filled portion. For the first

FIG. 1.—Half-cone meander niche incised in wall of older large chamber, Cave of the Mounds, Blue Mounds, Wis. Photograph by Charles Johnson.

hundred feet back, this tributary chamber has excellent conical niches in the lower part of its walls. Farther back, as in the big chamber, a red-clay fill appears, becomes higher with increasing distance back, has in it a meandering trench that niches back alternately into both limestone walls. This meander belt, as now developed, is nearly twice as wide as the clay-filled chamber.

It seems obvious that the pebbleless and flowstone-free clay fill is older than the present streams and that the streams would have removed it all had they not been hung up in the wall niches. The 4 feet of clearance noted in the big chamber seems probably a result of compaction,[4] the rock floor of the big chamber probably being much below the level reached by the streams, the clay fill therefore deep. The clay then records very quiet water up to the ceiling, a subterranean reservoir completely filled. The big chamber and the tributary branch are older than the clay, surely were not made under present conditions. Most of Smittle Cave has been inherited from a different type of ground-water circulation, and the stream of today is altering the original to its needs.

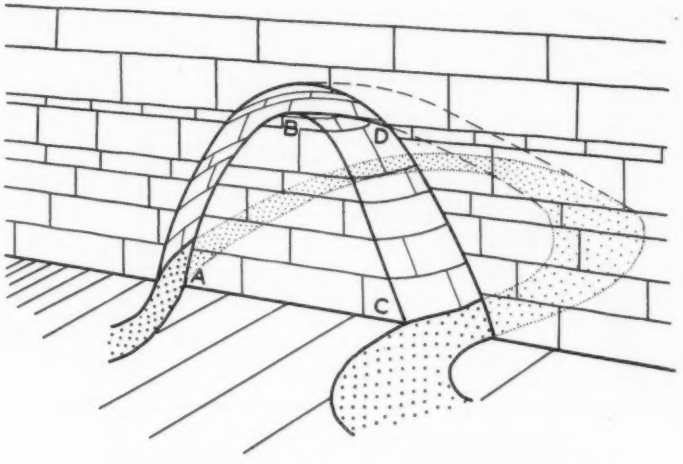


FIG. 2.—Diagram of half-cone meander niche in cave wall

Smittle Cave is one of nine[5] known to the writer where meander niches occur in the walls of large, fairly simple chambers. The others have no streams in the niches, and only five of them have relics of the

[4] For evidence of compaction of cave clays see p. 774.

[5] The others are Cave of the Mounds, Wis., Floyd Collins Crystal Cave, Ky., Truitt's and Mystery caves, Mo., Mark Twain Cave, Mo., Niagara Cave, Minn., Zane Caverns, Ohio, and Lookout Mountain Cave, Tenn. Davis reproduces a map of another such cave, with a stream now flowing in the niches as in Smittle.

clay fill. Cave of the Mounds, Wisconsin, has an amazingly complex development of meander loops back in the large chamber's wall rock. Complexity developed when the well-incised meander became enlarged enough to begin looping on itself, thus making more meanders as it deepened and undercut still farther into the wall. Because the ceilings of all these meanders remain, one may crawl down through a vertical range of nearly 15 feet here, being all the time out of the main chamber and within the narrow quarters of these intersecting,

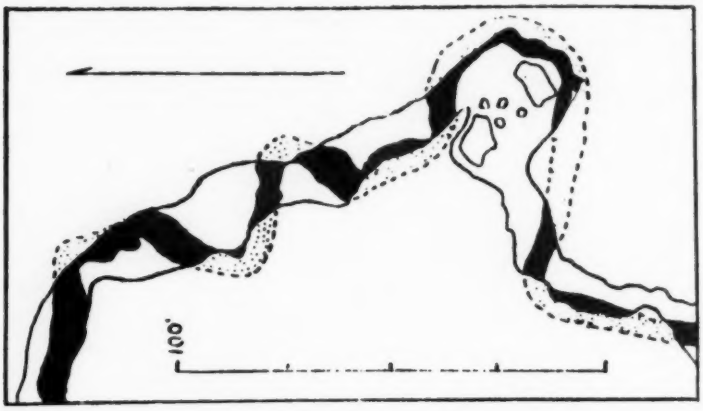


FIG. 3.—Meandering cave stream (after Davis)

superimposed, variously oriented, cone-shaped crescentic niches. If a meandering surface stream that is also deepening at a good rate were mapped every decade for ten thousand years, and the thousand maps were then accurately superimposed, *with the channels cut out of the paper*, the result would resemble this complex in Cave of the Mounds. Cave-stream meanders may thus have roofs which are the reverse of the familiar slip-off slope and essentially impossible with surface streams.

RUBY FALLS IN LOOKOUT MOUNTAIN CAVE, TENNESSEE

Another type of cave-stream behavior is excellently shown in this cave. A waterfall drops clear for at least 85 feet at the far end of a nearly vertically walled, dome-ceilinged chamber 150 feet long and

about 30 feet wide. This chamber is wholly unlike the 2,500 feet of low narrow cave one follows back to reach the dome. It is apparently the roofed recessional gorge of the cataract which has migrated only 150 feet from its point of origin.

But the waterfall springs clear from its lip, touches no rock on the way down, falls some 20 feet out from the base of the half-cylinder, cliffed re-entrant at the far end of the domed chamber. There is no Niagara Falls "Cave of the Winds" in weaker rock behind the falls. The recessional gorge's width is ten times that of the stream. Frost has never operated here to loosen fragments of the heavy-bedded limestone back of the falls. How, then, did the obviously responsible waterfall make the recessional gorge?

The details of the mechanism are clear when the long vertical groovings which cover all the walls are studied. Like those in Mammoth Cave's pits and domes,[6] they are surely solutional in origin. They are forming today, back of the fall, by the descending film of water held to the rock face by surface tension. Annetta's Dome, New Entrance, and other places in Mammoth Cave show this same descending film at work, in some places actually clinging to an overhang not steeper than 15°. But nowhere except at Ruby Falls has the final convincing evidence been seen; the deflection from vertical of these lapies-like groovings at the bottom of the side walls of the roofed gorge.

Directly behind the falls there is no deflection, but on both sides the groovings on the lowest 4–5 feet of wall height are a few degrees off vertical, descending away from the fall and toward the opposite end of the chamber. This trait exists also in the older and now abandoned groovings for the full length of the chamber. Furthermore, this belt of consistently deflected groovings is coextensive with a re-entrant niche by which the vertical wall with its vertical groovings is undercut for a maximum width of 3–10 feet back in the limestone,

[6] E. R. Pohl, "Development of Vertical Shafts in Limestone Caves," *Proc. Geol. Soc. Amer., 1935* (1936), p. 96; A. C. Swinnerton, "Cathedral Domes in Mammoth Cave," *Proc. Geol. Soc. Amer., 1935* (1936), p. 109. Domepits (Davis' term) also occur in Great Onyx Cave, Dossey Cave, Wilson Cave, Bat Cave, and Colossal Cave, near Mammoth; in Griffith Cave and an unnamed cave north of Cave-in-Rock, Ill.; in Truitt's and Mystery caves, Mo.; in Wonder Cave, Iowa, and in Niagara Cave, Minn.

at the base of the wall. Since the chamber floor slopes downward somewhat along its length toward the falls while the limestone is essentially horizontal, this niche and its inclined groovings cannot

FIG. 4.—Ruby Falls in Lookout Mountain Cave, Chattanooga, Tenn.

be an expression of different response of a particular layer to film solution.

Smoke introduced along this niche back of the falls proved the existence of two definite horizontal air currents in it, one on each side,

flowing out from behind the falling water. These currents, especially when the stream is in flood, obviously deflect the descending film and thus produce the inclined groovings. Spray from impact at the bottom of the falls is added to the film, and the niche is therefore the result of more solution at this lower level by the added water.[7]

Thus waterfalls may be only indirectly responsible for domepit chambers. Trickling films alone will do the work. In any case, the domepit is initiated by a subterranean piracy whereby water following a bedding plane high above the water table abruptly leaves that course at some point to fall to a lower bedding-plane route.[8] Several

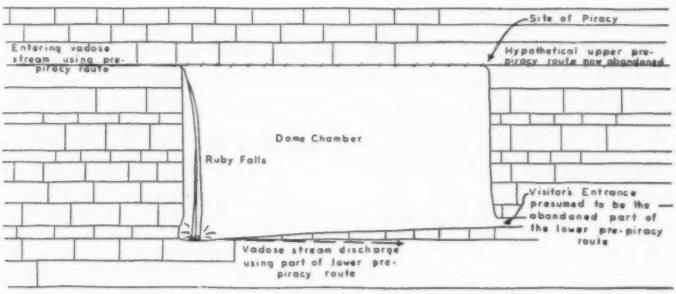

Site of Piracy
Entering vadose stream using pre-piracy route
Hypothetical upper pre-piracy route now abandoned
Dome Chamber
Ruby Falls
Visitor's Entrance presumed to be the abandoned part of the lower pre-piracy route
Vadose stream discharge using part of lower pre-piracy route

FIG. 5.—Diagrammatic projection in one vertical plane of water routes involved in making Ruby Falls dome chamber.

in Mammoth Cave cut completely through horizontal chambers intermediate between the upper and lower water-carrying levels, indeed, have receded across them, thus establishing the relative ages.

Domepits, therefore, are youthful vertical passages, as young as any solutional forms in the cave. For their initiation there must exist an older, two-storied system of horizontal channels. Growth of domepits and of their recessional gorges segments the older system and introduces a new type of chamber because a new type of groundwater circulation replaces an older one.

[7] Swinnerton (*op. cit.*) appreciates the importance of waterfall spray in making domepits.

[8] The Lookout Mountain stream course above and below the falls is unexplorable. The probabilities will be treated in a later section of this paper.

MISSOURI-ONONDAGA CAVE, MISSOURI, AND ITS STREAM

One continuous cavern here is crossed by a property line, and the two parts are shown under two managements and two names. The upstream part, Missouri Caverns, is a broad, elongated, dry chamber where entered, with a continuous flowstone floor over a clay fill. Minor subsidences in the clay, presumably caused by compaction, have cracked the flowstone and broken some stalactite-stalagmite columns.

A few hundred feet farther along the cave, this nearly flat floor ends and a descent of 75 feet is made down a steep clay slope to a stream entering the great room (90 feet to the ceiling) from a low

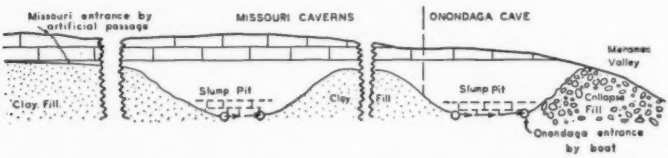


FIG. 6.—Diagrammatic projection in one vertical plane of features of Missouri-Onondaga Cave, Leasburg, Mo. Vadose stream twice enters and leaves through relatively small conduits in dolomite walls of the main cave. Slump pits occur where the stream uses the large chamber.

passage whose roof, farther upstream, descends to the surface of the water.

Still farther along the main cave, this stream leaves the big chamber by another low-ceilinged, untraversable passageway, and if one continues along the cave, he climbs up again to the top of the clay fill, having crossed a large, compound slump pit in the fill where the stream has undermined and removed the clay. Across the property line and now in Onondaga Cave, one again descends a steep clay slope to find the stream re-entering the bottom of the big chamber. For some distance beyond this, the stream remains in the main chamber. Locally, it goes under a low limestone roof or bridge on which are perched remnants of the clay fill. Finally, however, the stream again escapes from the big chamber, to reach daylight by way of another small passage. This is the entrance route to Onondaga. Along the large chamber, a little beyond the stream's point of de-

parture, a complete blockade of rock fragments cemented by flowstone terminates the big room essentially where it would otherwise emerge on the lower slopes of Meramec River Valley.

The large chamber's elongation strongly argues a former main subterranean drainage route. But no one is likely to hold that the present stream made it. However it was made, it later became filled with a pebbleless, flowstone-free lacustrine clay, just as did Smittle. The attack on the clay fill here has been made from below, instead of from above. The present stream found, or made, a largely new route to reach and to leave the large chamber, with proportions comparable to the stream itself, and apparently as low as the lowest portions of the big chamber. Just as the clay fill required different conditions from those now existing, so the big chamber required an even earlier and still different set of conditions for its origin.

Very similar is the intersection of another small stream-carrying cave and a large clay-filled chamber in Cathedral Cave a few miles distant. The only item not duplicated is the repeated entrance of the stream into and departure from the main cavern. The stream crosses once and at almost a right angle to the length of the large chamber.

ROARING RIVER–ECHO RIVER, MAMMOTH CAVE, KENTUCKY

In the lowest level of this great labyrinthine cavern system are four named water bodies, Lake Lethe, Echo River, River Styx, and Roaring River, all close together, all with the same level, all rising together with storm water from the drainage area tributary to them or with backwater from floods in Green River to which they discharge. Their basins are undoubtedly connected at levels lower than those ever reached in drought. Commonly, high mud and silt banks separate them along the cave-trail route, though at low-water time a limestone wall with four big windows or arches separates Echo from Styx where for several hundred feet they lie side by side. In low water, these four bodies are essentially lakes in the lower parts of a complex of large connected elongated chambers. There is no continuous descending floor and the current in flood time is due to surface slope of the water itself.

Roaring River chamber has only recently been explored.[9] Its

[9] Used as a part of the route to the "New Discovery" from 1938 to 1940.

ceiling for a few hundred feet is only 4 feet above lowest water-levels, and the maximum range of near-by Echo River in its high vaulted chamber is 54 feet. During much of the year, Roaring River is against its roof in this part of its course. Still farther upstream, no boat can pass under the ceiling even after the longest droughts.

In low water, Roaring River is a string of pools separated by floors of bedrock across which there is no discharge from pool to pool. Cliffed sides of the pools descend far below the water-level, so that for five of the pools boats must be used to make the trip up the river. In these pools and in the intervening stretches of rock floor are several pillars, some reaching completely to the roof, others cut in two or cut off at the top to make great pedestals interrupting the chambers. There are also three doublings of the chamber, longitudinal partitions separating them. These doublings continue for as much as 200 feet, making two tubes of the river route for that distance, the floor of one higher than that of the other. The partitions may be visualized as steeply inclined natural bridges. One has a window in it like the windows between Echo and Styx.

As estimated by D.C. Hazlett, of the National Park Service, some of the pools are as much as 50 feet deep. The walls descend steeply to the bottom and in the lowest 10 feet or so, side-chamber openings may be seen 40 feet below the water surface. Ends of the pool basins also descend steeply; the stretches of rock bottom separating them even overhang the water at low-level time. From this description it is clear that Roaring River has no continuously graded floor and that the pool basins are too wide, too long, and too deep for potholes as ordinarily defined. How, with only a 4-foot depth possible above some stretches of the rock floors, can the current keep these pool basins from filling with detritus?

The answer may lie in features of one of the pools. It alone can be waded. And its surface is reported by the surveyors for the "New Discovery" chambers to be 6 feet higher than that of the adjacent pool in either direction. The two pools, up and down stream, must have an adequate submerged connection beneath a natural bridge, itself all but submerged at low water, on which the shallow pool lies. Along this completely water-filled route, Roaring River moves its

traction load of chert fragments and Pottsville quartz pebbles, keeping the deep basins open.

This curiously irregular chamber-channel of Roaring River has a ceiling which, like the floor, fails to parallel the surface of a continuously descending stream. In flood, the low ceiling noted is nearly 50 feet below what would be the free surface if the chamber were as high as that of Echo. Furthermore, the connection between Roaring and Echo rivers is concealed below the lowest levels of the water. In other words, the ceiling of the Roaring River route in one place is continuously submerged, yet it separates stretches with high ceilings.

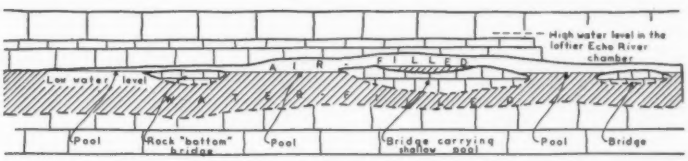


FIG. 7.—Diagrammatic longitudinal profile along part of Roaring River, Mammoth Cave, Ky.

Echo River at low water has maximum known depths of 40 feet, while Styx, on the other side of the perforated partition, is only a few feet deep.

The only features in this complex of subterranean water courses that belong to a stream seeking grade are the mud and silt deposits along parts of Lethe and Styx. Here the chamber is much too capacious for the stream and the quiet eddy places in flood backwater are being filled with bars alongside the main current.

Enlargement of passages, shown by strongly developed current-made flutes,[10] is occurring on the floor, walls, and ceiling of Roaring River in the constricted places. These flutes strikingly resemble current ripples in sand, being invariably steep on the downstream side, more gently sloped on the side facing the current. Their existence on the ceiling strongly argues for their solutional origin.

This interpretation of the Mammoth Cave stream considers that

[10] J. H. Maxson, "Fluting and Facetting of Rock Fragments," *Jour. Geol.*, Vol. XLVIII (1940), pp. 717–51.

its complex of chambers has been inherited from an earlier and different type of ground-water circulation, that the complex could never have been made under today's conditions, that solutional enlargement in some places and depositional reduction in other places are endeavors of the present river to adapt the inherited complex to its needs.

CUDJO'S CAVE AND ITS STREAM

Cudjo's Cave in the extreme western tip of Virginia is on the east side of Cumberland Gap, its two entrances 75 feet apart vertically and its stream emerging 165 feet below the upper entrance. There are still higher portions of the cave without entrances from the mountainside. Their relative altitudes are unknown to the writer.

The limestone in which the cave is developed has a maximum dip of 30° and beneath it is a thick shale formation, both showing well in the cliff and highway cuts. That part of the cave system below the upper entrance lies throughout in the same stratigraphic horizon—up in the limestone, not at the shale contact.

The solutional cave system has suffered much by rock fall from the sloping ceilings. Solution chambers below these tracts of fallen blocks are now largely obliterated. One must reconstruct the original system from wall and ceiling remnants with undoubted solutional outlines. When so reconstructed, Cudjo's Cave becomes a sloping spongework of irregular chambers and large blind pockets, with little control by jointing, with only one repeating feature that resembles the chamber of the strike stream now draining the cave at the lowest open level.

That repeating feature is a nearly horizontal, smooth-walled tube along the strike, averaging twice as wide as high, cutting through tight places in the pockety spongework, truncating projections of that spongework, ignoring large pockets lateral to its course, crossing in the air where large chambers lie in its course, possessing current-formed flutes which all the spongework chambers lack and a smooth, level ceiling cut across the edges of the dipping beds. Different tubes can be identified from these characters at vertical intervals of 10–20 feet throughout most of the cave; some can be followed for considerable distances. Interruptions in their continuity are due (1) to ex-

istence of earlier chambers, the tube opening to be seen on opposite sides of such, and (2) to fall of rock involving portions of the tube.

These tube chambers are interpreted as made by the free-flowing gravity stream of the cave, working at successively lower levels as the surface valleys were deepened. It crossed the older, irregular spongework chambers on a detrital fill that has been largely removed as the strike stream dropped down the dip to successively lower positions. The interpretation needs only evidence that the spongework cave exists, though filled with insoluble debris, below the pres-

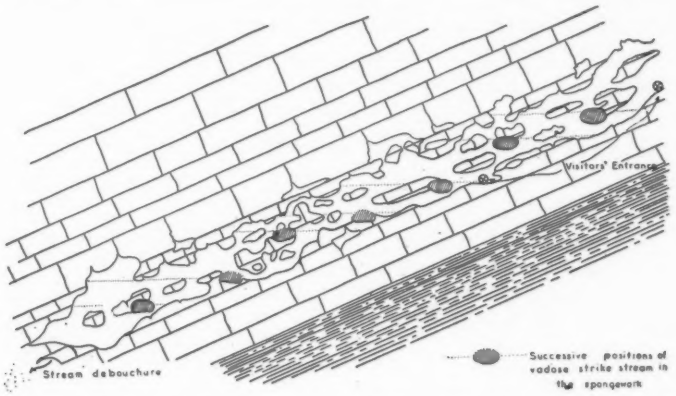


FIG. 8.—Idealized dip section through Cudjo's Cave before alteration by rock falls from roof.

ent stream. Since most caves of the writer's experience record two episodes of cave-making, separated by one of cave-filling with clay and silt, the inference used here to explain the tubes seems justified.

POKERVILLE CAVE, WISCONSIN, AND ITS STREAM

There is no natural opening to this cave, though nowhere is the ceiling of the 500-foot-long, main upper chamber more than 10 feet beneath the surface. This chamber is a tube 6–7 feet in diameter, somewhat sinuous in ground plan, oriented with the length of the broad ridge crest under which it lies. It is entered from a highway cut through the top of the ridge. Except at the far end, this chamber has no alluvial filling. Instead, the tube floor for the first 400

feet is trenched by an untraversably narrow slot in dolomite, at least 15 feet deep near the entrance but gradually shallowing farther back until it disappears. One travels along shelflike remnants of the tube bottom, crossing the slot opening or straddling it repeatedly.

This slot opening is itself sinuous in the tube floor and its reverse curves greatly increase in size with depth, the slot inclining alternately to one side and then to the other in a meander belt which is four or five times as wide as the tube.

The last 100 feet of chamber length is floored with sand. This fill gradually rises toward the ceiling until further progress is impossible. The fill is essentially a very much elongated alluvial fan bearing rill marks and containing a few bits of vegetable matter. The roof here is only 4 feet thick.[11] Traced downgrade, the rill-marked sand surface descends into the head of the winding floor slot and can be seen repeatedly at increasing depths nearer the entrance.

This is the stream of Pokerville Cave—a temporary flow from heavy rains on the field above the cave. There is no sink on the surface, but a passageway down through the roof rock must exist to make this entering concentration of soil water.

The vadose stream has made the sinuous floor slot, is still deepening it, perhaps is still lengthening it. Additional evidence exists near the entrance where a branch tube chamber, similar to but smaller than the main one, has no flow of vadose water and no floor slot. Also near the entrance, the main tube itself loses the vadose stream down to a deeper level and, for the few tens of feet between entrance and the point of this loss, has no slot in the floor.

The tube chambers are early cave forms. One was inherited by the vadose discharge and remarkably modified after the conditions that determined the tubular chamber had disappeared.

Other cases of chambers with meandering trenches cut in the bottom of tubular passages are in Big Hurricane Cave, Arkansas, and Mammoth Cave, Kentucky. The Hurricane tube is diversified with large ceiling and wall cavities.[12] Numerous smaller tubes, without a

[11] A. G. Fischer, A. C. Mason, and W. S. Twenhofel, "Survey of Pokerville Cave, Blue Mounds, Wisconsin," *Trans. Wis. Acad. Sci., Arts Letters*, Vol. XXXII (1940), pp. 243–50.

[12] See pages 710–11.

trace of running water on their floors, connect with the trenched main tube. These are parts of the earlier cave system, surviving unmodified because untouched by the later vadose stream now using the trench. The meandering trench is said to be 2 miles long. Several tube openings also exist in the cliff face at the mouth of Hurricane, unquestionably parts of a cave network abandoned as the outside valley has been deepened.

The example in Mammoth is a small branch chamber off Robertson Avenue, near Fairy Spring. The original chamber, several times as wide as high, determined the original meander belt, but the width

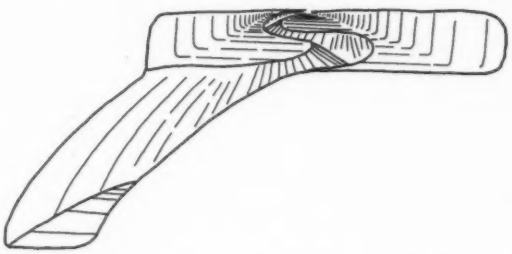


FIG. 9.—Meander trench in bottom of small chamber, near Fairy Spring, Robertson Avenue, Mammoth Cave, Ky.

of this belt increased as the curves enlarged during the deepening. No stream now uses the meandering trench.

Davis[13] tells of a similar cave, though smaller than any of the above, reported to him by A. C. Lane, and asks that trenches cut in the bottoms of larger chambers be considered a criterion for two-cycle history, uplift having terminated the phreatic work of the first cycle and initiated the vadose work of the second. The argument would be even more convincing if the floor of the large chamber had high places in it with the trench limited to those places. One such case occurs in one of the 1938 "New Discovery" chambers of Mammoth Cave. The explanation offered is that a vadose stream, downcutting from the top of a clay fill in the older capacious chamber, found itself superimposed on the high place and was forced to trench

[13] *Op. cit.*, p. 566.

here into bedrock. The clay has been removed subsequently from both sides of the high place, and a small "watergap" type of gorge now records this sequence.

MERAMEC CAVE, MISSOURI, AND ITS STREAM

The entrance to Meramec Cave is a fine archway, 25 feet high, 50 feet wide, in a vertical cliff of the Meramec River Valley. The cave floor of alluvium is about 30 feet above river low-water and is occasionally inundated by river floods. One may drive a car 900 feet back in the cave on this flat, smooth floor, the cavern proportions remaining essentially as at the entrance. Back here the ceiling gradually descends until it is at the prevailing floor-level. But at this place the floor also descends, disappearing beneath a pool under the lowered ceiling. The pool occupies an inverted siphon in the cave course. Beyond it, the chamber and its floor for about 250 feet farther are identical with the 900-foot length already traversed.

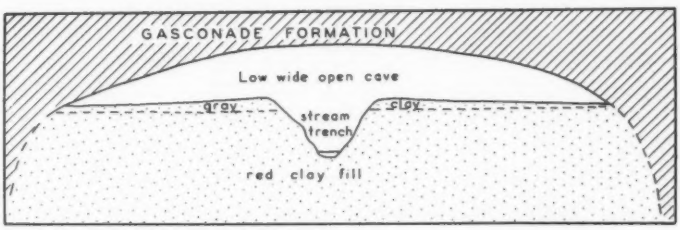
Here, about 1,200 feet from the entrance, the cave joins another chamber of similar proportions but with a lower clay floor, the two disposed in ground plan like the arms of a Y, the traversed chamber being the right-hand arm. A clear rippling stream approaches the junction along the stem of the Y and continues down the left-hand arm, its channel trenched in a red-clay fill, its bottom covered with chert gravel. This stream is known to emerge as a spring through a series of mere cracks in the base of the river cliff not far from but lower than the spacious archway entrance. Thus both arms of the Y reach the river valley bluff a quarter of a mile beyond the junction.

The ceiling of the left-hand chamber arm descends gradually downstream from the junction until, at full width, the flat ceiling makes contact with the clay floor. In the floor, the stream trench is 15 feet deep, cut in red clay. The top of the clay fill, however, is a gray mud or silt, with definite natural levees margining the ravine-like channel.

The significant items regarding Meramec Cave, thus far presented, are: (1) the downstream (riverward) bifurcation of the capacious stem channel into two, (2) the clay and mud fill in all parts of the Y, (3) the stream trench 6–15 feet deep in the clay alone, (4) descent of the ceiling of the left-hand arm to the level of the fill, that is, the

vanishing of that chamber beneath a complete fill, and (5) escape of the stream *through the roof* of the left-hand chamber.

The gray mud and silt overlying the red clay in the trench slopes and making the levees is recent Meramec River material, a record of back water at high flood stages. The red clay is older than the present stream and, farther back up the stem of the Y, has no overlying



[FIG. 10.—Cross section of Meramec Cave at left end of Fig. 11

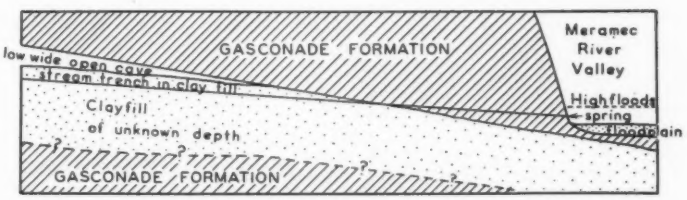


FIG. 11.—Longitudinal section in downstream end of Meramec Cave, Stanton, Mo.

gray mud. Very obviously the stream did not make this cave and is only removing the fill in the part we have examined. Conditions notably unlike those of the present obtained when the bifurcating chamber system was dissolved. After they vanished, but before present conditions were established, the big chambers received a deposit of red clay whose depth is unknown.

SUMMARY OF PRESENT-DAY STREAM WORK IN CAVES

Seven different relationships of streams to the caves in which they occur show that the streams are clearly altering caves which they did not make and could not have made under existing conditions.

Two epochs of cave-making are recorded in each case. The second one is still in progress and therefore a minimum of debatable inference is involved in explaining it. Summarized, the seven types are as follows.

1. *Smittle.*—A capacious chamber of the first epoch became mud-filled. The fill today is being removed or has been removed by a free-surface meandering stream which started flowing on the top of the fill and which, during its deepening, laterally incised the rock walls of the mud-filled chamber, becoming locally entrenched in these walls to make half-cone slots.

2. *Pokerville.*—A chamber of the first epoch later became used by a small free-surface meandering stream. A mud fill may have antedated the stream, but a fairly flat rock floor to the first epoch chamber would serve as well. The stream eroded a narrow trench or slot in the rock floor, its curves enlarging as it deepened until a sinuous gorge was made, the slip-off slopes having reciprocal overhanging walls like the half-cone wall slots of (1). Meandering, however, is not an essential; nor is continuity of the gorge if the first-epoch chamber floor has higher places onto which the vadose stream may have become superimposed from a mud filling.

3. *Lookout Mountain.*—Along two different bedding planes, two horizontal passages or networks of passages, with adequate vertical separation, were developed during the first epoch. Noteworthy capacity was not needed at either level, nor were the systems connected by any vertical shaftlike opening. After each had attained essentially its full existing development, a new condition was introduced, the lowering of the water table to or below the lower system. Consequent on this, the upper system became segmented by a leakage down to the lower one. Thus subterranean piracy made a dome-pit, entirely vadose in origin (second epoch), but it required two phreatic systems (first epoch) for its occurrence.

4. *Missouri-Onondaga.*—As in (1), a capacious chamber of the first cave-making epoch existed. Similarly, this chamber was filled with lacustrine clay before the water table was lowered. Then, upon the lowering, a vadose stream made or came to use a route that entered and then left the lower part of the clay-filled big chamber. The work of this stream has been to undermine the fill, deep slump

pits recording the locus of this work, extensive clay flats elsewhere lying close up under the ceiling.

5. *Roaring River.*—A chamber complex made up of lateral branches from the main, of side-by-side members of the main (pillars and windowed partitions separating them), and of imperfect and incomplete stories (natural bridges separating them) dates from the first epoch. A large gravity stream (free-surface in part) comes to use portions of the complex after the water-table lowering has occurred. The occupancy is of such recent occurrence that the stream's only success in grading its route has been in depositing silt and sand back in less-used portions of the inherited complex. Bridges, partitions, and pillars surviving from the earlier cave-making epoch still interrupt and subdivide the stream. Some bridges are submerged except in low-water, some ceilings are far below flood-levels reached by the stream both up and down current from them.

6. *Cudjo.*—A complex of irregular interconnecting chambers was developed during the first epoch along a tilted formation. The complex was a kind of very coarse spongework with tabular dimensions. This complex later became filled with mud, though still beneath the water table. Then came a gradual migration of the water table downward through the tabular assemblage of clay- and sand-filled cavities and with it (perhaps on it) a free-surface stream flowing along the strike toward the deepening river valley outside. This stream superposed a new type of chamber on the earlier irregular cavity assemblage—a tubular conduit recorded now by horizontal half-cylinders or nearly whole cylinders cut through the coarse spongework, interrupted by empty spaces where larger first-epoch cavities existed and the stream across them was walled and floored with sand or clay, now gone. A succession of such fragmentary tubular courses records downdip shiftings to lower positions as the outside stream valley has been deepened. The detrital fill, even if no remnants now exist, is nevertheless recorded by the alignment of the fragments of direct tubular routes.

7. *Meramec.*—A capacious chamber of first-epoch origin became filled with clay while still beneath the water table. The chamber had a slight gradient, at least in its ceiling. Deepening of a surface river valley near by then lowered the water table enough to bring much

of the chamber into the vadose zone and to give it a vadose stream, but the lower portion still remained below this plane and thus could have no such stream. The surface valley offered the cave stream an escape at flood-plain level, but because the first-epoch chamber ceiling here was below that level, escape had to occur through the chamber roof. Thus, though the clay fill suffered much erosion upstream in the cave, its erosional surface descended less along the cave than did the chamber ceiling and near the place of stream escape through the roof, the fill today still remains complete to the ceiling. The cave-stream route thence to the outside valley is barely large enough to traverse by crawling in the water and is wholly vadose in origin. The large chamber beyond the point of stream escape must exist, completely clay-filled, beneath the valley's flood plain.

PHREATIC FORMS AND PATTERNS

Ten types of cave forms impossible of formation by free-surface stream erosion will be discussed under this heading.

THE SPONGEWORK OF MERAMEC CAVE

Meramec was the last of the seven caves selected to show the work of present cave streams. The origin of the inherited chambers each stream is occupying was given little attention. With the background already presented, we may now take up its consideration. Meramec will serve this purpose as satisfactorily as any cave known to the writer.

If one goes upstream from the junction of the two capacious chambers of this cave, along the stem of the Y, he travels in a clay-floored chamber of fairly uniform cross section, finding only one laterally constricted and one vertically constricted place in nearly half a mile of length. Terrace remnants and wall-pocket fillings of red clay show that the present clay-floor surface has been eroded by the cave stream in a fill once complete to the ceiling.

Two stream-carrying tributary chambers and one with only the beginning of a water course join the main chamber in that half-mile. The streamless one has a hard red-clay fill so close to its ceiling that travel is possible only by bending double and, farther back in it, only by crawling. A tiny gully, nowhere more than 20 inches deep, is incised in the top of this fill.

Of the other two, one is almost ideally developed to show relations between pre-clay cavities and the passage made by the stream as the clay is being removed today. This tributary route has a uniformly graded stream bed, covered with chert gravel. For most of the length examined, its width is not much more than that of the little stream. However, this narrowness is repeatedly interrupted by irregular widenings to two or three times that of the narrow stretches. The widenings contain remnants against their back walls of a red-clay fill that once reached completely to their ceilings.

On climbing these steep red-clay slopes of the subterranean ravine, one finds amazing complexes of small, interconnecting solution chambers in the limestone, separated by amazingly intricate perforated partitions and remnants of partitions. The relations are as complicated as those of the pores of a sponge. It is possible to crawl over the remnants of red clay in them and in places to crawl over the *top* of the subterranean ravine. None of the cavities is linear like the accompanying stream course. No system of relationship among them is detectable, other than that described by "spongework." The wide places are parts of an original spongework where adjacent cavities became larger and larger until partitions completely disappeared. The tributary ravine is the result of a gravity flow that succeeded deposition of the clay.

This gravity flow of a free-surface stream has developed along those better-opened parts of the spongework which would lead it continuously downgrade and out to the Meramec River. The ravine-like passage through the spongework is no older than the river valley, while the spongework itself antedates the surface valleys of the region. Spongework in the limestone back from chamber walls and ceilings, genetically the precursor of the larger chambers, has been encountered in excavating the entrance route to Round Spring Cavern, Missouri, and two stairway routes in Meramec. Fully 30 per cent of the caves known to the writer contain somewhere in them a spongework complex, several of them also showing a younger trench cut through the complex. Well known to many is Mammoth's "Fat Man's Misery" where a winding gorge has been cut through an original spongework by a later vadose stream from Grecian Bend to the Valley of Humility. The average size of the cavities and the

range in size vary from cave to cave, but the solutional work of water without definite current, without surface gradient, without air above it, is convincingly recorded as occurring before a red-clay filling epoch.

The picture drawn thus far does not account for the linearity and cross-sectional uniformity of the big chambers constituting the Y. They look like the consequence of gravity-directed current, yet certainly (1) are not the work of the present stream, (2) are too large for the subterranean discharge which the adjacent upland can provide, and (3) are aberrant in their bifurcation if their current flowed toward the present valley. Likewise, no place has been provided yet in the sequence outlined for the similarly big linear, uniformly cross-sectioned chambers of Smittle and of Missouri-Onondaga. A more extensive factual background is desirable before treating this question.

The southern part of Wind Cave, South Dakota, has a gigantic spongework in which the overlapping and connecting cavities are full-sized cave chambers. Stairways and winding trails ascend and descend through the maze. Your guide is likely to indicate a great hole in the ceiling and remark, "We were up in that room five minutes ago," or one in the floor, saying, "We'll be down there shortly." Two joint systems affect the cave pattern, but their influence is all but lost in this region of giant pocket chambers.

THE NETWORK OF MARK TWAIN AND CAMERON CAVES, MISSOURI

These two caves occur low in the valley slopes on either side of Cave Hollow which enters the Mississippi Valley less than a mile from the caves. They are very similar caves in most characteristics, particularly in ground plan. Each shows a remarkable control of passageways by the jointing. At least three different joint sets are involved. At some intersections five and even six passages lead radially away. The visitor's route in Mark Twain Cave makes a complete circuit by turning left at five successive intersections. Several other circuits could be laid out without much duplication of passages used. No wonder that Tom and Becky got lost; so did the writer's party when it first ventured out of the trail-marked area. There are nearly 11,000 feet of passages in this cave within the 15

acres of the mapped area. Cameron Cave is said to have even more footage in its network.

The floors of both caves are everywhere of clay and sand, locally covered with stream gravel. Except for a few slump pits, the surface of the fill in passages near the valley slopes is uniformly about 15 feet above the flood plain outside. The slump pits in Cameron Cave are 40–50 feet deep, indicating a fill much deeper than the height of the open passages, a downward extension of the chambers and slots well below the stream-level outside.

Chambers result from the intersection of passages or from the doubling of a joint for a few tens of feet where both members have been enlarged by solution. The island made in the second case may be a bladelike wall less than a foot thick, with windows in it, or may be only an elongated pedestal-like rock projecting up through the fill, the top of the island having been dissolved away. Most openings are too narrow to be called "chambers" or "rooms." Many are too tight to traverse easily, though most have adequate height. Heights of average passages (above the top of the fill) are about ten times their widths. They become even narrower toward the top, mere slits along the joint plane. Several curious bridgings occur in these slots, very narrow slabs standing on edge or end, attached on top to one side of the slot and on the bottom attached to the opposite side, or even to the same side.

Mark Twain Cave has three openings on the valley slope and in addition nineteen former openings, all now completely closed by an inside talus of hillside waste and by flowstone deposits. Cameron Cave has an unknown number of such intersections of cave network and valley slope, probably as many as its sister-cave across the valley, but only one is now open. In all the blocked intersections of passages with valley wall in both caves, it is obvious that only slope-wash water has deposited the flowstone which cements the talus debris.

Remnants of the clay fill on high shelves in both caves record a former completely filled condition. In some of Cameron's closely spaced parallel passages separated by windowed or perforated walls, one may cross back and forth by climbing over "divide" ridges of clay 6–10 feet high, remnants recording (1) the pre-fill existence of

the network much as it now is, (2) the original completeness of the fill, and (3) the post-fill removal of more clay from main passages than from minor ones.

After realizing (1) the extent of each of these caves back in the hill on opposite sides of the valley, (2) the horizontal and vertical limitations of each along these valley slopes, and (3) the excellent development of the network pattern by which so many "blocks" are completely bounded by "avenues," "streets," and "alleys," it becomes

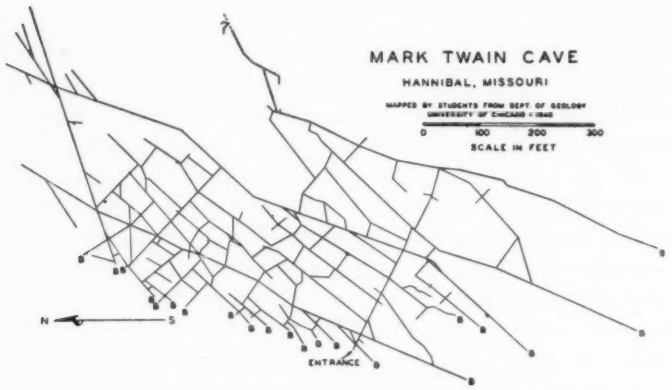


FIG. 12.—Map of Mark Twain Cave, Hannibal, Mo. Each passage end marked *B* is determined by a blockade of hillside waste and flowstone. Except for the *?*, all other passages are terminated by a gradual rise of the clay floor.

impossible to explain the caves as subterranean routes of Cave Hollow Creek or as entirely subterranean gravity-stream courses. It is not difficult to see in them two remaining portions of one large cave system older than Cave Hollow Valley—a system whose central portion has been destroyed by deepening of the Hollow. Again we find a cave system out of harmony with present drainage, surface drainage in this case.

With Mark Twain and Cameron caves may be grouped Crystal Lake Cave, Iowa, Ohio Caverns, Ohio, parts of Wind Cave, South Dakota, Cave Hill Cave, Illinois, and Cave of the Winds, Colorado. They are all alike in possessing complete networks developed along the intersection of bedding planes and joints before the clay-fill epi-

sode occurred, before surface streams had cut down to the cavernous horizon, before gravity streams could work at their levels. They are phreatic cave systems, their passages developed in all directions along which water under hydrostatic pressure in the formation could move at the time they were made.

Though neither Mark Twain nor Cameron Cave has an ordinary vadose cave stream today, each has had one in the past. The record in each is a gravel deposit occurring only in certain passages, and there overlying the present surface of the clay fill. In Mark Twain, a good showing of the gravel is in the southerly narrow prolongation of Grand Avenue. It is here a foot thick and has yielded snail shells, hackberry seeds, and a 3-inch pebble of diorite, all doubtless brought in by Cave Hollow Creek through a near-by now blockaded intersection of the passage by the valley slope. It occurs on the floor of two or three closely associated passages in one part of the cave, showing that the stream was aggrading, not deepening in the clay fill, at the time of deposition.

Cameron's gravel record of a vadose stream includes smooth vein-quartz pebbles derived, like the diorite, from the glacial drift outside. In Cameron, as in Mark Twain, the gravel deposit becomes thinner and the pebbles smaller farther into the system until the record is lost. Not only did the gravel-depositing stream have to wait until the cave system was complete and the valley was deepened to within about 15 feet of its present depth, it also had to wait until the clay fill had been lowered to the present floor-levels of both caves.

Entrance of surface streams into pre-existing cave systems and their exit farther along have been described by Clyde A. Malott.[14] They are the basis for his invasion theory of cavern development. But these two Missouri caves, unlike the Indiana caves Malott describes, suffered no great solutional enlargement from the experience, and most of their passages show no record whatever of the episode. The streams shortly abandoned their temporarily adopted routes and returned to the surface valley.

[14] "Lost River at Wesley Chapel Gulf, Orange County, Indiana," *Proc. Ind. Acad. Sci.*, Vol. XLI (1932), pp. 285–316, and "Invasion Theory of Cavern Development," (abstr.), *Proc. Geol. Soc. Amer., 1936* (1937), p. 323.

HORIZONTAL CHAMBERS OF GRAND CAVERNS, VIRGINIA
IN NEARLY VERTICAL BEDS

The Conococheague limestone here, with dips of 83°–86°, is cut by a few vertical joints almost at right angles to the strike of the bedding. Most of the cave chambers extend horizontally along the edgewise beds. The depth of the clay fill that constitutes the floor is unknown. Chamber heights vary considerably. Perhaps 30 feet is a good average, though some are nearly 100 feet above the floor. Widths also vary but rarely exceed 30 feet.

The dark-blue limestone has numerous thin layers, seams, and lenses of yellowish, clayey, less soluble material, showing plainly on

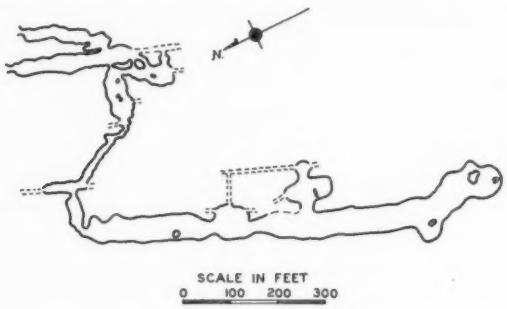


FIG. 13.—Map of Grand Caverns, Grottoes, Va. (after W. M. McGill)

freshly broken surfaces and better brought out by differential response to solution. No cave in the writer's experience shows so strikingly the recession of edges of more soluble layers to make reentrant niches and slots, separated by projecting ribs of less soluble rock. This is expressed in all possible degrees of magnitude. Blades of limestone less than a quarter of an inch thick may project 2 or 3 inches from the wall, niches 2 inches wide and 6 inches deep may indent the wall. Where the less soluble material is unevenly distributed, not in regular laminas, a spongelike character of the wall rock has resulted.

From this minor etching there are all gradations to full-sized cave chambers themselves. Mostly, the projecting ribs stand a foot or so in relief, but there are great blades hanging from 30-foot ceilings

well down toward the present floor and buttresses of equal magnitude projecting into chambers along the strike. Near Jacob's Ladder, the cave is actually double because of a less soluble stratum perhaps 10 feet thick with more soluble limestone on each side. In places this separating partition is intact from ceiling to floor, but most of it is perforated by windows and doors of almost every possible shape, size, and location. In places the partition fails to reach the ceiling, making a great wall along the middle of the double cave. Elsewhere, it hangs like a thick curtain from the ceiling, failing to reach the floor. The windows may be mere peepholes or they may be great ragged openings with slablike spurs reaching up into them from the floor or down from the ceiling or in from the sides. One chamber is the greater in one place, the other in another.

Caves like Grand Caverns, though undoubtedly former water courses, could never have been fashioned by free-surface gravity streams. The solutional work must have been done under completely saturated conditions. There are no forms recording or even suggesting a definite current. There are abundant forms which a current could not produce, or hardly tolerate. We know nothing of the true floor of Grand Caverns but if the explanation advocated be correct, that floor should be largely a replica of the ceiling. Grand Caverns' horizontal extent in nearly vertical beds suggests water-table control in some way, though that table must have been above the highest solutional ceilings. The cave is therefore older than the valley of South River, a part of the Shenandoah Valley.

Baker Caverns, Pennsylvania, in nearly vertical beds, shows a bladelike curtain made by a less soluble stratum. Here "The Cathedral" is a double room above head height, the two parts separated by the great hanging blade but possessing in common a continuous, uninterrupted floor. Wonderland Caverns, Pennsylvania, has bladed projections hanging from the ceiling, projecting from chamber ends and, in the "Devil's Den," protruding up through a clay-fill floor. Several other caves with good but less marked development of high-angle grooving, ribbing, ridging, and perforated partitioning are also known in the folded Appalachians.

BEDDING-PLANE ANASTOMOSES IN THE STE GENEVIEVE FORMATION

A. C. Swinnerton comments on "a wide range of variation, from one limestone region to another, in both kinds and associations of [karst] physiographic forms."[15] The writer, agreeing with him, would extend the idea to cave forms also. A part of the thesis of the writer's paper on caves in the Galena formation[16] was that the common repeating shape of these caves, where of phreatic origin, is a high, narrow, straight slot along a joint. Similarly, many of the twenty-

FIG. 14.—Cross section of bedding-plane anastomosis in the Ste Genevieve formation. Cliffs of Ohio River, Cave-in-Rock, Ill. Photograph by G. S. Monk.

four caves and many cliff faces in the Ste Genevieve formational group, seen during this study, show a cavity feature that has rarely been found in any other limestone. It is the anastomosis of a multitude of small, sinuous passages along a bedding plane, the earliest attempt at cave-making in the formation.

Generally, member tubes of this anastomosis show in cross section only as a row of subequal holes in the bottom part of a stratum. The guides at Mammoth Cave call them "postoffice boxes" and

[15] "Limestone Terranes," *Proc. Geol. Soc. Amer., 1936* (1937), p. 117.

[16] J H. Bretz, "Caves in the Galena Formation," *Jour. Geol.*, Vol. XLVI (1938), pp. 828–41.

Hovey, in *Mammoth Cave of Kentucky* (1912), calls them "pigeon holes." The total cross-sectional area of a group may be as great as that of the limestone separating them, but commonly is less. Rarely are they large enough to crawl into. Individual holes commonly have a bulbous cross section, higher than wide, narrowest close to or at the flat base, widest close to the rounded top. Commonly also, if *in situ*, a clay fill covers the bottoms.

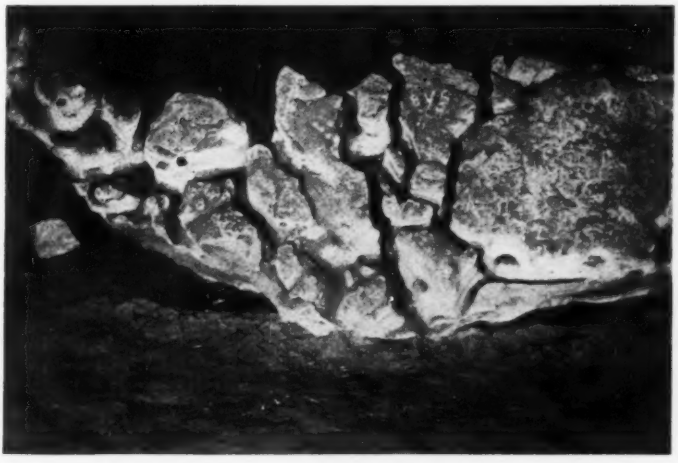


FIG. 15.—Bedding-plane anastomosis in the Ste Genevieve formation. Fallen roof block, Mammoth Cave, Ky. Photograph by Lyman Huff.

In the endwise view of them in chamber walls, the anastomosing relations are not conspicuous and might be overlooked. Fortunately, numerous exposures of their complicated ground plan occur in flat ceilings and on fallen blocks. Figures 15 and 16 show the common pattern. They are unknown in solutional ceilings, occurring only on those produced by the falling-off of slabs. Thus they are not a result of any chamber-enlarging action, nor can they be younger than these chambers. They antedate the larger units of a cavern system. From selected portions of them, larger passages later have had their origin.

The bulb cross section is a curious shape. Curious also is the fact that the enlargement of tubes of an anastomosis has been upward

into the overlying stratum, there being almost no downward penetration into the layer below. The explanation offered for this takes account also of their primitive origin. Earliest water movement deep within the Ste Genevieve formation found most favorable routes along certain bedding planes. This movement was very slow, was essentially laminar. The water had no transporting ability even after the tube anastomosis had begun to develop. Insoluble residue from the limestone therefore settled and remained on the bottom. Colloidal material in it made a sufficiently tight film to protect the limestone below from solution. This film mounted the lower sides and there preserved almost the initial widths. Enlargement of the tubes was therefore mostly at the top and upper sides. The bulb cross section resulted.

FIG. 16.—Bedding-plane anastomosis revealed by fall of roof slabs in Serpent's Hall, Mammoth Cave, Ky.

Most of these bedding-plane anastomoses never evolved farther because selected routes developed here and there in them, took all the discharge and brought circulation in the remainder of the anastomosis to an end. Finally a lowering of the water table drained them. In some a complete clay fill was introduced late in their history and survives today. Some still later have become routes for vadose water and are closely related to the domepits and the high, narrow, winding, vertically grooved slots of Mammoth, Great Onyx, Colossal, and other caves. These relationships are treated more fully later in this paper.

JOINT-PLANE ANASTOMOSIS OF WIND CAVE, SOUTH DAKOTA

It might well be presumed that in solutional widening of any joint crack to become a cave chamber, the initial solution would be irregular and a complex of small interconnecting tubular conduits would be formed, like those along the bedding planes in the Ste Genevieve limestone. Only one slightly opened joint, however, has yet yielded anything closely comparable to the bedding-plane anastomosis, and this joint[17] is more nearly horizontal than vertical. Incipient solutional widening of vertical joints is shown in at least three vertical walls in Carlsbad Cavern where weakening along the joint has caused rock falls late in the cave's history. The exposed surfaces bear intricate designs of shallow half-pockets, undoubtedly the record of solution along these joints before the breaking-away occurred. The patterns do not suggest descending vadose water. But neither are they the anastomosing system of crooked channels typified in the ceiling pattern in Serpent's Hall, Mammoth Cave.

Wind Cave, South Dakota, has the best example known to the writer of solutional widening of joints, where all work was abandoned with the passing of the phreatic episode, no vadose stream ever inheriting and using the passages. But the work was farther along than the simple anastomosis stage.

The stairway at the north end of Wind Cave descends at least 100 feet in a narrow, vertical, joint-determined chamber with ragged horizontal moldings and re-entrants etched from the strata edges. But it is not a clerestory chamber. In many places the two walls are still tight together. Some of these places are simple, short bridgings, others are more like floors between stories, still others involve considerable thicknesses of strata, perhaps with horizontal holes through them along the joint trace. Three or four "stories" can be seen from some viewpoints along the stairway.

There are doublings, triplings, even quadruplings of the joint in places. One keystone or wedge, a big vertical slab serving three closely spaced, imperfectly opened joints, still hangs in place in the great slot. Some keystones have fallen. One such is 20 feet high and 30 feet long, but, owing to narrowness of the slot, it still stands nearly

[17] Mammoth Cave Route 6, near Violet City entrance.

upright. Some of these slablike keystones have holes dissolved through them from one opened joint to the next. Most of them are as ragged in all outlines as are the walls. And what is true of this largest phreatic joint chamber is true of many other joint-determined chambers and passages in Wind Cave. In some places the character of the solution cavities suggests the spongework of Meramec, without its later vadose ravine cut through the complex. Flat, thin sponges they are, locally. They also somewhat resemble the network of Mark Twain Cave, if that be visualized as on edge, the horizontal strata then determining the different chamber units, the joints determining the general plane of the system. A slight development, in Wind Cave, along another vertical joint system at right angles to the dominant one described, helps the comparison. In all three caves the cavities obviously are impossible consequences of any vadose stream.

WALL POCKETS

Solution-made indentations in cave walls, apparently fortuitous in their distribution and unrelated to joints or bedding, are fairly common forms[18] that have received scant attention. Their outline in the wall is generally rudely circular, their shape resembling the interior of a round-bottomed kettle. They may be deeper than wide. Sizes range widely. If closely grouped, they may so overlap that no unpocketed wall surface remains among them and the aggregate suggests the spongework already described. But typical wall pockets have only solid limestone back of them instead of a spongework complex of as yet unexposed complete cavities. Wall pockets are not older than the wall in which they occur, as are the spongework cavities. Nor are they younger, as are the meander niches and half-cone slots.

Some walls have only a few widely spaced pockets, others have a crowded aggregate of them. Small pockets in the sides or bottom of big ones are not rare, but still smaller ones in the small ones are. The complexity of such a wall defies detailed description. The writer has not been able to find specific causes for their locations, either in struc-

[18] At least half of the caves examined in this study possess some showing of wall pockets.

ture or composition of the wall rock or in local impingement of circulating water. It can only be said that such a surface required, for its making, a complete water fill in the chamber and an absence of definite current, that the chamber's growth was by the "eating-out" of limestone in the pocket concavities, destruction of exposed partitions going on as the pocketing penetrated farther into the wall rock. Wall pockets are phreatic features.

CEILING POCKETS

There are fewer pockets of this category (i.e., without apparent cause for localization) in ceilings than in walls, but their occurrence with associated wall pockets requires the same explanation. If the water table were so little above the phreatic cavernous zone that droughts bared these pocketed ceilings, trapped air would have remained for some time after return of a normal water-table level. Minimum solution, rather than maximum, would have occurred in them. The argument favors ceiling-pocket origin below the lowest water-table levels of the time.

The only difference between wall-pocket and ceiling-pocket forms appears to result from a different angle of penetration into the strata involved.

FLOOR POCKETS OF CARLSBAD CAVERN

Very rare are exposed bedrock cave floors. Fallen rock fragments, clay fill, stream sand and gravel, flowstone—all conspire to conceal them. And of the exposed floors, most are in vadose stream beds. For present purposes, we want to compare phreatic floors with phreatic walls and ceilings. The writer had studied nearly fifty caves before he chanced to find them first in Baker Caverns, Pennsylvania. The best display now known is in Carlsbad Cavern, New Mexico.

Carlsbad Cavern's chambers have never had a general fill episode. Though in the upper levels the bedrock floors are covered with debris, there are places deeper in the great cave where the desired exposures occur. For Carlsbad is, throughout all chambers shown to visitors, entirely a phreatic cavern.[19] These floor exposures ("The Boneyard") show a limestone surface as ragged with intersecting pockets as any walls or ceilings. Holes as much as 12 feet deep have

[19] As Davis said it would prove to be.

a

b

FIG. 17.—Floor pockets in "The Boneyard," Carlsbad Cavern, N.M. Photographs by M. T. Bull.

been dissolved out. Pinnacles and blades between the pockets are residuals where the attack, for some reason, was less vigorous. The pockets and pinnacles are as grotesquely shaped as any in the ceiling. Chambers with these floors are generally very large compound pockets themselves and could be turned upside down without changing the aspect. Carlsbad's history has passed directly from the earliest or phreatic episode to that of dripstone deposition, generally the latest in any cave's history. The clay-fill and vadose-stream episodes have been omitted.[20]

Though many caves in the writer's experience show striking development of pockets on top and sides of chambers, and a few on bottoms, none equals the display in the lower chambers of Carlsbad. The best showing of all is in an east-west joint-determined chamber off the Dining Room, now used, unfortunately, for the toilets and for a general junkroom by the concession company. All conceivable combinations of pocket overlap and intergrowth, of minor pockets in larger ones, of wasted partitions, of residual spurs and blades, of fragile bridgings in horizontal, and of inclined and vertical positions, are here. Yet this superlative display is but a maximum development of the pocket type of cave-wall form.

JOINT-DETERMINED WALL AND CEILING CAVITIES

These forms generally are larger than the pockets and certainly are farther from equidimensional. Some of them are essentially short blind-end chambers with the trace of the causal joint identifiable in ceiling and end wall. Expectable is the common ceiling slot along a chamber's length. Expectable where the joint doubles or triples are the two or three close-set ceiling slots, such as Virginia (Melrose) Caverns, Virginia, possess. But equally common are transverse slots and cavities where cross joints intersect the main chamber. These usually carry the walls farther apart as well as the ceiling farther up. The effect is often that of a series of high closed chambers on the cross joints, except where perforated by (connected by) the continuous chamber. The pattern is the beginning of a network. Solution seems to have penetrated much higher in making the

[20] As far as the writer has seen this cave, down to 3,600 ft. A.T.

cross-joint chambers of some caves because of initially greater widths of joint cracks.

An excellent showing of this relationship is in Horseshoe Bay Cave, Wisconsin, where the ceiling rises from an average of 4 feet along the connecting passage to as much as 30 feet in the cross-joint chambers, and the width increases from 12 to 30 feet along the lengths of the cross chambers. There are eleven such intersecting combination ceiling-and-wall cavities in 380 feet of length of the low

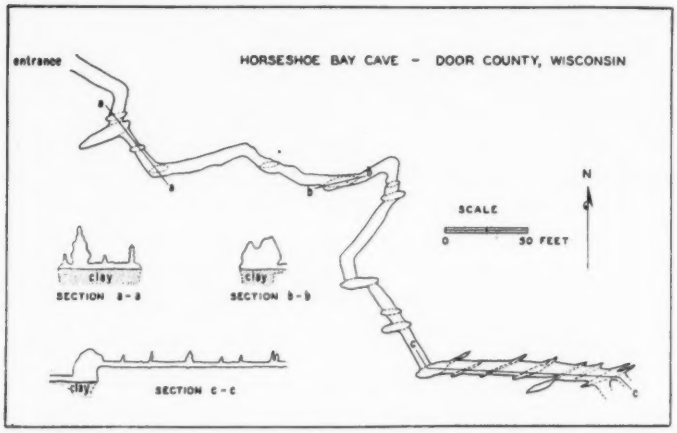


FIG. 18.—Map of Horseshoe Bay Cave, near Egg Harbor, Wis.

continuous connecting passage. Some of the cross chambers are no longer than the diagonal width of the connecting passage, thus are only ceiling cavities. Ten of the eleven lie on the N. 70°–80° E. joint system which the connecting passage almost wholly ignores.

Indian Cave, Tennessee, also shows a succession of elongated domelike ceiling cavities crossed at high angles by the long stream-occupied main cave chamber. Some of these carry the ceiling up to 60 feet above the stream, three times the average height of the connecting chamber. Lost Cave, Pennsylvania, has blind-end wall cavities extending back from the main chamber along both the strike joints and the dip joints. Some of them are almost slots, some are almost tubes, yet all end against limestone, never were contin-

uous routes of a completed network. Lost Cave also has joint-determined ceiling cavities which penetrate as far as do the wall cavities, as much as 20 feet beyond the main chamber's sides and top.

FIG. 19.—Joint-determined wall cavity in Lost Cave, Hellertown, Pa. Cavity is 20 feet long (deep), its average diameter 2 or 3 feet; the hammer is 7 feet back in the cavity. Photograph by Lyman Huff.

Cavities of this category are probably more common in ceilings than in walls, reversing the ratio among the pockets. All record attack from the cave side. They are not tributary chambers, nor

are they distributary routes. Like the pockets, they are records of solutional work in enlarging the main chamber before air had ever entered the cave.

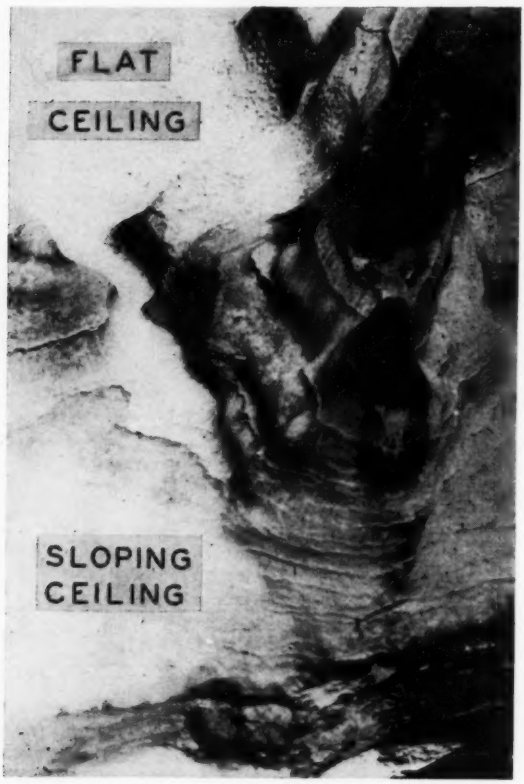


FIG. 20.—Joint-determined ceiling cavity in Wyandotte Cave, Wyandotte, Ind. Photograph by Paul Herbert.

If joint-determined wall and ceiling cavities are of phreatic origin, floor cavities of the same type might be expected to exist, though most of them, like floor pockets, will be buried in debris. The writer knows of only two cases of well-exposed passage floors above which

are strung good ceiling and wall cavities on cross joints. One of these—Sylvan Avenue in Mammoth Cave—has cross slots in the floor rock corresponding with the associated wall and ceiling cavities. The other case is beneath chambers 12–18 of Horseshoe Bay Cave, on a higher level than the detritus-floored chambers 1–11. The joints show in the floor but are not widened or deepened a single inch. Confident that the wall and ceiling cavities are the product of phreatic solution, the writer believes that some special conditions prevented solution downward at this place. Most probable seems to be the accumulation of a colloid-rich residual clay on the floor, unremoved because of slowness of movement of the water.

CEILING TUBES AND HALF-TUBES

These features were first shown to the writer by Clyde Malott, in a network cavern at Wesley Chapel, Orange County, Indiana. They are commonly only the upper part of what obviously once were complete tubes situated at the intersection of a joint and a bedding plane. Their diameters range from a few inches to a few feet. The larger chamber beneath seems clearly to be a later development, essentially a deepening and widening of the earlier tubular water course. The tubes are interpreted by Malott as primitive caves—survivals, along with the network pattern of the cavern, of a wholly phreatic system. The larger, lower part of the chamber Malott believes is vadose, for all these Indiana caves contain either a present-day stream on the floor or an unquestionable record of one.

Later, the writer found very similar ceiling half-tubes and segments of entire tubes in Crystal Lake Cave,[21] near Dubuque, Iowa, two-storied in some cases, a smaller above a larger and the slotlike joint-determined cave passage below both. His interpretation made all parts of such passages phreatic and contemporaneous in origin, a kind of flat vertical spongework with dominant horizontal elongation of the openings along the joints. Conditions had favored greater enlargement of the lower members and most of the higher tubes had thus become segmented. Fall of ceiling rock was also recognized as a cause for disappearance of the lower parts of some half-tubes.

Though the later history of this Iowa cave differs from that out-

[21] "Caves in the Galena Formation," *op. cit.*

lined by Malott for Indiana caves, both interpretations consider the tubes themselves to be phreatic in origin. The forms occur in more than a dozen caves known to the writer and are genetically the same as many complete tubular openings and passages without a larger passage or a chamber below them. For them to form, an intersection of bedding plane and joint must exist in the rock and a slow hydraulic circulation must then utilize the intersection.

CONTINUOUS ROCK SPANS ACROSS CAVE CHAMBERS

Bridges are rock spans across chambers whose flattish surfaces are no steeper than 45°. Between 45° and verticality, such spans will be considered partitions. Windows may occur in both, may also exist in otherwise continuous floors which are also roofs for immediately lower chambers. Marked tabular form in bridges is commonly an expression of stratification; in partitions it commonly expresses jointing, because most strata are more nearly horizontal than vertical, and most joints are steeply inclined.

Solutional attack on both sides of the span is required for its origin, and windows appear as the span wastes away. The question of most interest regarding bridges is whether the two sides were attacked simultaneously or in sequence. If the latter, then water flowed over before it flowed under. Only complete submergence, that is, only phreatic conditions, can provide for simultaneous attack. A vadose stream under special conditions of steep gradient and favorable bedrock partings, similar to those at Trick Falls, Glacier National Park, might conceivably leave a bridge across its deepening subterranean route, but wide bridgings (measured along the passage length) over low-gradient, free-surface cave streams can hardly be ascribed to that stream's work. Several such bridgings in one low-gradient chamber[22] seem wholly impossible by this origin and are as satisfactorily explained by phreatic solution as are the joint-determined wall and ceiling cavities, the grooves and ridges on cave walls, or the joint-plane anastomoses. When such bridges were made, water was circulating in all cracks at the same time, most solution occurring where most favorable partings existed or most soluble rock

[22] As along Roaring River, Mammoth Cave.

was reached by the water. The bridges are residuals of the more protected or later attacked or less soluble portions of the originally continuous rockmass.

FIG. 21.—Partition span in Historic Indian Cave, Franklinville, Pa. Orientation is determined by joints. Bedding dips across the slots and partition. Photograph by Lyman Huff.

Partitions are residual masses, like bridges, whose form was originally determined by bedding or joint-plane partings. Here, also, simultaneous solutional attack from both sides seems clearly indicat-

ed. No vadose stream could conceivably continue for long to deepen a double channel and leave an intact thin island wall reaching to the ceiling of the double chamber. Furthermore, windows in such partitions rarely have rounded outlines that strands of a cave-floor stream would make if the partition, dividing the current, became perforated at stream-level. Grand Caverns' partition windows look more like the hole left in a shattered glass pane where the sash and putty still hold long projecting blades and slivers. The comparison is for form, not origin.

Pillars are special forms of partitions. A vadose stream divided by a pillar must certainly be attacking the base more vigorously than the top, can hardly do other than promptly destroy the form, can no more be held accountable for its development than for the making of partitions.

SUMMARY OF PHREATIC FORMS AND PATTERNS

We have now considered the following five solutional cavity patterns: spongeworks, networks, horizontal chambers in vertical beds, bedding-plane anastomoses, and joint-plane anastomoses. No free-surface stream is known to be making such patterns. There are no associated records to show that such streams ever did make them. In most chambers there is no record that such streams have ever touched these cavities. Knowing also the limitations of free-surface stream work, it seems safe to say that the patterns are impossible for such streams to have made.

We have also considered four types of forms which solution has left on cave walls, ceilings, and floors: pockets, joint-determined cavities, tubes and half-tubes, and continuous rock spans. In similar manner, we have concluded that the cave streams we see at work never could have made them. All these features thus become criteria for origin below the water table of such caverns as possess them. They are first-epoch features.

SPECIFIC FORMS AND MARKINGS RECORDING CURRENT FLOW

INCISED MEANDERS IN CAVE WALLS AND CEILINGS

In the preceding description of Smittle Cave is a presumably adequate treatment of the incision of a cave-floor stream's meanders

into already existing cave walls. In the description of Pokerville Cave, meanders are shown to have trenched more deeply in a rock floor, and to have swung more widely, than the original chamber's height and width. Under a later heading will be found an account of meander incisions in cave ceilings. A summary note is here made of the conditions under which these meander records must have been formed.

1. A capacious chamber existed before the meanders developed.

2. The meandering cave stream was in all essentials identical with meandering streams in surface valleys.

3. The stream began meandering largely on a fill of insoluble waste.

4. Where the stream was removing the fill, only wall incisions could be made, the shape of which was a half-cone, right-side up.

5. Where the stream was flowing on a rock floor, a complete meandering trench, identical (except for overhanging walls), with incised meanders in a surface valley, resulted.

6. Where the stream was aggrading, as in Endless Caverns (p. 742), the wall incisions were inverted half-cones, and, if the fill finally reached the ceiling, the complete meander pattern became incised in it. Original chamber capacity was increased by such ceiling solution, but the added portion is easily differentiated from the pre-fill portion.

HORIZONTAL GROOVES AND RIDGES ON WALLS OF CAVES IN FLAT-LYING BEDS

The consequence of differential solubility of strata is less marked on cave walls in flat-lying limestones than in high-angle beds because, as shelves grow wide and thin, they are broken off by their own weight. Furthermore, they may be less marked in one's consciousness because familiarity with surface cliffs on which weathering has made bedding-determined projections and recesses may subconsciously incline one to overlook their significance in cave walls. But weathering of this kind is rare in caves, and where paired and continuous grooves and ridges are markedly developed they are commonly associated with other forms and patterns of phreatic origin.

Where, however, the grooves and ridges record differential attack, that is, lateral swinging of a free-surface stream on a lowering cave

floor, the grooves are discontinuous and they alternate from one side to the other. Thus a stratum edge, traced along the wall, will be recessed for a few feet or tens of feet, beyond which it will be flush with the wall and may even project a little. Grand Avenue in Mark Twain Cave shows such discontinuous grooves associated with marked widening and with stream gravel. Niagara Cave shows such grooves, passing in places into the Smittle type of incised-meander wall niches. Cave of the Mounds has these grooves, definitely arcuate, associated with its remarkable group of incised meanders.

Where the groove fails to follow the stratum edge but cuts across to another stratum because of either stream gradient or stratum dip, vadose origin is clear.

DOMEPITS

The description of Ruby Falls in Lookout Mountain Cave will serve as an introduction to the domepit type of chamber. Examples of this type in Mammoth Cave have been discussed by several writers[23] and in Mammoth's numerous and impressive domepits, all but one of the significant facts known to the writer may be found. The general picture already presented in this paper embodies: (1) two functional bedding-plane water courses, one above the other, (2) a later segmentation (piracy) of the higher by vertical descent to the lower along a previously unused joint plane, (3) solutional enlargement largely by water trickling down the joint-plane faces, and (4) horizontal elongation of the domepit like the lengthening of the gorge below a receding waterfall.

Domepits should not be visualized as all of the simple form implied by the name or described for Lookout Mountain. The ground

[23] The most recent comments and theories are found in the following papers: Marvin Weller, "The Geology of Edmonson County," *Ky. Geol. Surv.* (1927), p. 59; A. K. Lobeck, "The Geology and Physiography of Mammoth Cave National Park," *Ky. Geol. Surv.* (1928), p. 390; Davis, "The Origin of Limestone Caverns," *Bull. Geol. Soc. Amer.*, Vol. XLI (1930), p. 600; J. H. Gardner, "Origin and Development of Limestone Caverns," *Bull. Geol. Soc. Amer.*, Vol. XLVI (1935), pp. 1255–74; Pohl, "Development of Vertical Shafts in Limestone Caves" (abstr.), *Proc. Geol. Soc. Amer., 1935* (1936), p. 96; Swinnerton, "Cathedral Domes in Mammoth Cave" (abstr.), *Proc. Geol. Soc. Amer., 1935* (1936), p. 109. Gardner, Pohl, and Swinnerton ignore the method of origin suggested by Davis and, though disagreeing among themselves, all suggest items which the writer believes must be embodied in a final explanation.

plan may be exceedingly complicated. The features consistently present are two: great height as compared to width, and vertical walls with vertical grooves.

One common ground plan, little noted in the literature, is a narrow, irregularly sinuous vertical slot. It is not a domepit in form or part of a complex of overlapping, intersecting domepits. It is simply a vertically convoluted gashlike parting (not a joint plane) whose walls bear the diagnostic vertical groovings. Most of these slots, however, connect with a domepit. Elbow Crevice, the passage leading to the waterfall in Annetta's Dome, passages associated with Minerva's Dome-Sidesaddle Pit, Gorin's Dome, Washington Dome, Bottomless Pit—all these are examples. A genesis in common with the domepits is an inescapable conclusion.

If origin of the vertical sinuous slot required leakage of water down a joint from some higher to some lower chamber, and if that point of leakage retreats upstream, then sinuosities of the receding fall's slot must be the consequence of sinuosities in the course of the upper stream. This seems to allow us to visualize a sizable, traversable cave chamber above. But there are many complexes of these slots so closely associated that a separate chamber originally above each cannot be allowed. Nor is the idea acceptable as an explanation for the capacity of the great domepits themselves.

Study of the ceilings of domepits solves the difficulty. These ceilings are marked with the phreatic bedding-plane anastomoses characteristic of the Ste Genevieve limestone. They are like dozens of ordinary chamber ceilings where roof-rock slabs have parted along, and fallen from, such a weakened bedding plane. The upper water course therefore was not in a traversable chamber; instead it was a member of a bedding-plane anastomosis.

This conclusion is acceptable, however, only if it can be shown (1) that the ceiling-tube anastomosis is the original top of the dome, not the result of later stoping up to such a horizon by the fall of roof blocks, and (2) that the outlines of the domepit conform to the pattern of dominant tubes in the ceiling anastomosis.

Bottomless Pit establishes both these points and adds a surprising explanation for domepit enlargements along the course of vertically grooved slots. As seen from the trail, the flat ceiling is margined al-

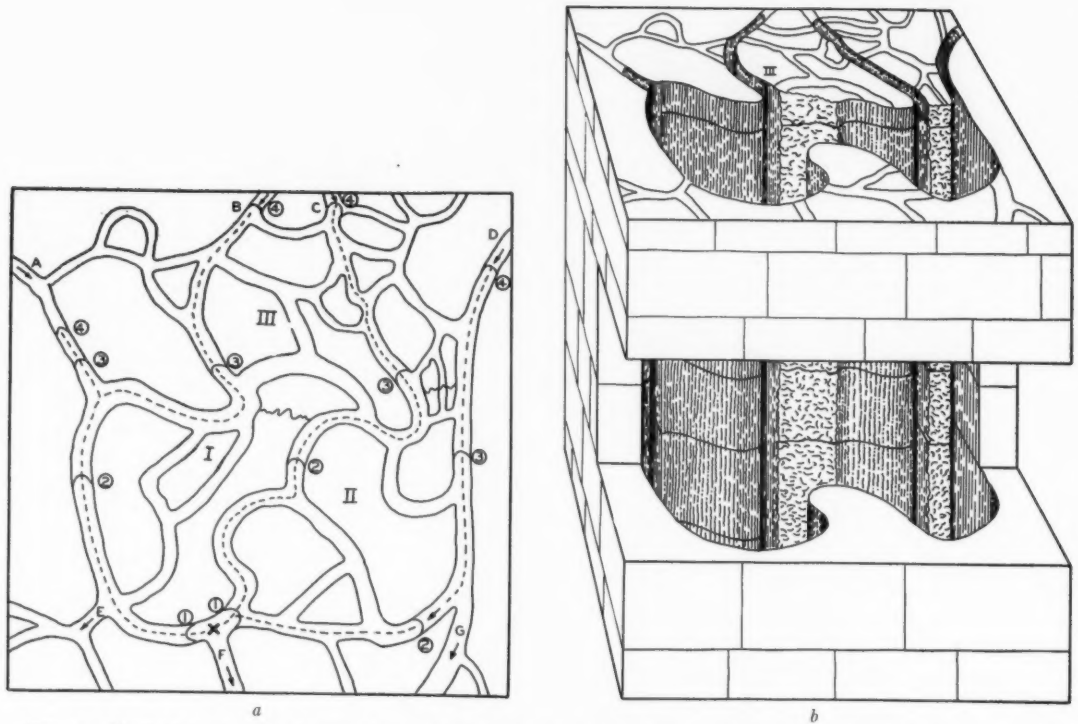


FIG. 22.—Idealized developmental stages of a core-block domepit in the Ste Genevieve formation. (*a*) Ground plan of the bedding-plane anastomosis. Vadose water, entering by routes *A*, *B*, *C*, *D*, and leaving by *E*, *F*, *G*, finds a new escape route down a joint at *X*. The initial slot is lengthening in two places at stage (*1*). Before stage (*3*) has been reached core block I has been made and presumably has begun to fall. Block II becomes unstable shortly afterward, and, at stage (*4*), block III is nearly ready to fall. (*b*) Blocks I and II have disappeared, leaving a domepit of dumbbell cross section with sinuous vertical slots leading back to the sites of falling or trickling water at stage (*4*). An older, linear chamber has been partially intersected by the domepit.

most all the way around by the upper half of a dominant tube member of an anastomosis. Water falling from a leakage in this tube cut a deep vertical slot that, in horizontal lengthening, nearly closed on itself. A column was thus cored out—a column that had no adequate support at the bottom where the water entered the lower of the two required horizontal courses. This column fell, in sections,

FIG. 23.—Part of a domepit complex in Mammoth Cave, Ky. Observer is looking diagonally upward. Flat ceiling is result of recent fracture along bedding plane. Pit on the left is traceable into two sinuous slots.

and most of the core blocks have been dissolved away at the bottom of the pit.

Not all of it has gone, not all sections fell clear to the bottom. The footbridge across Bottomless is built on such a fallen section, all of 20 feet along its bedding, lodged diagonally across the shaft. From a point perhaps 50 feet below the trail-level, Bottomless is seen to have a very complicated shape, possessing several great empty coalesced shafts and many smaller ones, with fallen core blocks lodged diagonally across narrow places. Only an anastomosing upper water course, with several tubes functioning simultaneously, could have made this complex of intersecting domepits or could have cut out these great core blocks.

FIG. 24.—Profile along narrow chamber and domepit in Wonder Cave, Decorah, Iowa

Several named avenues of Mammoth that had no part in carrying water to or from domepits or vertically grooved slots have been cut in two by growth of these features. Lively and Blacksnake avenues are thus transected by Bottomless Pit. Gorin's Dome cuts the avenue by which the dome is approached. The avenues simply happened to lie between the upper and lower functioning courses and at an adequate angle to the course along which the receding slot or domepit lengthened. Some of the avenues also have a sand fill, similarly cut in two. At Gorin's Dome, current-bedded sand records a southward flow while the domepit was made by a later, *but higher*, stream falling to a lower level and its slot receding eastward. When Minerva's Dome–Sidesaddle Pit recession began, the lower level was approximately that of Blacksnake (though surely not that particular passage). On reaching Blacksnake, the fall abruptly doubled in height by cutting as deep below the Blacksnake floor as its top was above. The only point to be made here of this fact is that the snaky avenue was not a functional part of the domepit-making.

At the bottom of Mammoth Dome, whose "Ruins of Karnak" columns are but surviving re-entrants between cored-out coalescing shafts, lie sections of fallen columns, the groovings of their sides at right angles to the bedding. Since fall and reorientation of the cores, drip water has developed a second set of groovings, oriented down the steepest dip of the fallen blocks' upper surfaces. As it happens, these new groovings are almost parallel with the bedding. Here removal of fallen cores is recorded with no cave river required at the bottom. In the Cathedral Domes group, there is a similar example.

The one significant feature of domepits not seen by the writer in Mammoth Cave was found in Wonder Cave, Iowa. It is an upper passage leading to a fine domepit chamber, and in both passage and domepit there is a clear sequence of associated phreatic and vadose features. The visitors' route, only recently opened, has been made possible by considerable excavation along the sides of the upper passage, a very narrow, rock-floored waterway.

The floor descends about 25 feet along the 500 feet of this artificially widened, fairly straight passage, but the ceiling remains horizontal. Thus the height increases to the end where the domepit can be viewed from a platform about 30 feet below its ceiling and 50 feet above its bottom.

The ceiling of the passage carries a faint but perfectly definite half-tube, a remnant of a phreatic route along the intersection of a joint and a bedding plane. But no phreatic route needs a continuously descending rock floor nor is any vadose, free-surface stream likely to demand a horizontal ceiling over its sloping floor. The passage has had experience with both types of circulation, a late vadose stream cutting the bottom out of an original phreatic tube and producing the descending rock floor. This explanation is amply sustained by the occurrence of numerous flutes and half-potholes in the walls. Their existence records turbulence, their orientations record a downhill flow.[24] Absence of incised meander niches in the walls indicates a good current in the vadose stream.

The domepit is an elongated, gorgelike chamber resembling that at Ruby Falls, with a subsidiary smaller pit in the bottom. Its walls carry a very interesting pattern of both flutes and groovings, the flutes recording essentially horizontal flow, the groovings a record of vertically falling water films. At the far end of the dome (the oldest part), groovings reach from top to bottom; at the near end (junction with the narrow passage), groovings fall about 25 feet short of reaching the dome top. Above these groovings are the flutes which thus cover a triangular area of the upper wall, widest at junction of the narrow passage and continuing upstream on that passage's walls. All flutes record the same direction of flow. Those in the

[24] On a later page, an *uphill* flow recorded by flutes will be described.

upper wall of the dome are indubitably older than the groovings directly below them and must have been made before the rock bottom was destroyed by domepit growth.

FIG. 25.—Vertical groovings on wall of domepit, Mystery Cave, Lanagan, Mo. Photograph by G. F. Shepherd.

It seems obvious that the vadose stream which inherited the phreatic tube (now a half-tube) found a joint-plane vertical descent at the far end of the domepit and, until it ceased to flow, simulta-

neously elongated the domepit and deepened the joint-and-bedding determined tube. The fall provided conditions for steepening the gradient along the 500 feet of narrow passage but itself removed far more limestone during the vadose epoch.

The subsidiary pit is at the near end and penetrates about 20 feet deeper into the bottom. It records either an abrupt lowering of the water table or, more probably, a late discovery of further possibility

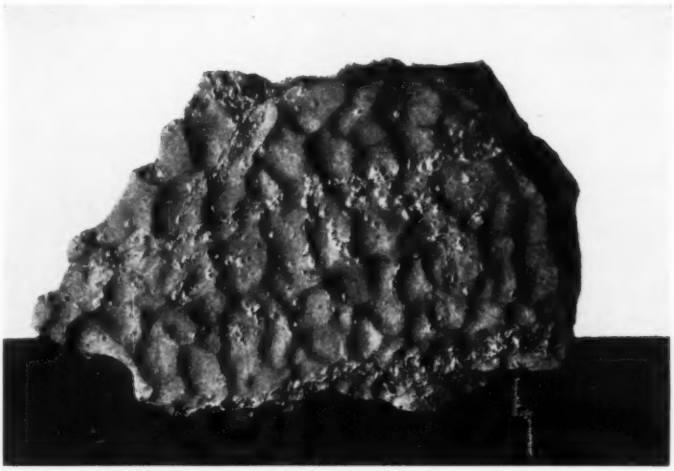


FIG. 26.—Flutes on Ste Genevieve limestone from Shetlerville Cave, Hardin Co., Ill. Current flowed from left to right.

of vertical descent toward it. The bottom of a domepit is not necessarily determined by the water table of its time. Sand or chert gravel, a cherty or otherwise less soluble layer, or even a local pool will terminate the fall-and-trickle mechanism at any level above the regional water table. Nor are capacious chambers necessary either above or below the fall; indeed, the writer knows of no domepit and only one vertical slot which has both. That slot is Elbow Crevice, Mammoth Cave, where the fall began in the upper chamber (Gothic Avenue) and retreated to incise a lower one (Gratz Avenue). The beginning in Gothic was largely a coincidence. Had Gothic been a functional

part of the circulation when Elbow Crevice was formed, the Crevice would have been lengthened *along* Gothic.

The interpretation of Wonder Cave's domepit requires, for a complete picture, one more item. There should be a surviving remnant of the segmented phreatic tube showing in the far end. There does exist at that end a narrow vertical opening, but it fails to reach up to the level of the phreatic tube along the ceiling of the narrow passage. It may be, however, that the earlier circulation followed the joint down to an intersection with a lower bedding plane and that this place in the tube determined the origin of the later vadose fall.

Straight, elongated, gorgelike domepits, such as Wonder's, record phreatic water courses along joints. Only the Ste Genevieve type of bedding-plane anastomosis can produce the Bottomless Pit type of compound domepits.

An apparent disharmony in the theory for Ste Genevieve domepits needs a few words. The bedding-plane anastomoses are announced as phreatic in origin, yet they are asked to function as the upper passageways after the regional water table has fallen far below their level. The explanation is that at this later stage, they collect vadose water en route to the saturated zone, perhaps from a surface sink, and may carry it laterally for a considerable distance before it escapes to lower levels.

The domelike arching at the top of these great vertical shafts in the Ste Genevieve limestone does not carry groovings. There is excessive raggedness to these uppermost walls—the result of deepening by vadose water in different members of the anastomosis similar to the deepening in Wonder's narrow passage near the junction with its domepit.

That the Ste Genevieve bedding-plane anastomoses exist throughout the formation, far from large chambers and therefore not subsidiary branches of them, is shown in the walls of vertical slots that have migrated back from the older horizontal avenues. The sinuous passage leading back to Annetta's Dome has revealed several dry levels of these anastomoses.

Dossey Cave and Wilson Cave, in the Mammoth Cave region, are hillside domepits made by water descending the present valley slopes and finding, en route, joint-plane entrance into bedding-plane anas-

tomoses. Dome tops of these shafts are far below the top of the Ste Genevieve limestone and, of course, never have reached higher in the formation.

FLUTES

These markings may be described as small, shallow, asymmetrical cups, close set and even overlapping, with the steep side invariably upstream. Or they may be described as unsymmetrical, irregularly placed, short ridges, in the ground plan of which continuity of crest lines is more nearly attained across the current than with it. Earlier in this paper, they were compared with aqueous current ripples. The comparison is good, both for form and for orientation. They appear to be equilibrium forms demanded by bottom vortices.[25] The sizes, the proportions of height to width, and the steepness of lee-ridge slopes seem to be determined by character of the current rather than that of the limestone.

Flutes are believed by the writer to be solutional rather than abrasional forms, for they occur on walls and ceilings as well as on floors, and their surfaces may be interrupted by projecting unabraded chert nodules and fragile silicified fossils.

Where the dunelike current ripples of bed-load sand migrate downstream, these limestone flutes must migrate upstream if they travel at all. Removal of material, rather than addition, changes their form and location, and their steeper lee slope seems to record maximum solution there.

Unlike the lapies groovings, flutes cannot be used to prove that vadose conditions existed at the time of their formation. Their value is in the record of definite current and of direction of flow. As a criterion for direction of flow in now dry chambers, they appear to have been overlooked by most earlier students.

POTHOLES

Described by Malott and noted by a few other observers are potholes in some cave-stream beds. Most of them are eddy holes,[26] their sizes within the range shown in eddy potholes of surface streams. Cherts projecting from their walls suggest solutional origin,

[25] See Maxson's article, already listed, for a more detailed analysis of the flute-making mechanism.

[26] H. S. Alexander, "Pothole Erosion," *Jour. Geol.*, Vol. XL (1932), pp. 305–37.

though perhaps silt-laden water was a factor. A free-surface stream is making them today in the cave at Wesley Chapel Gulf, Indiana.[27] By inference, similar streams made abandoned potholes in now dry chambers, since the causal eddies of growing potholes are features of free-surface streams and all known, abandoned potholes were excavated downward, none were ever drilled laterally or upward.

A remarkable showing of potholes exists in "Pothole Alley," a high narrow passage off Roaring River chamber, Mammoth Cave, a part of the exploration route to the 1938 "New Discovery" chambers. The passage is walled with half-potholes from bottom to top, some of them nearly 10 feet in diameter. Fifty per cent of them have a central cone-shaped mound in the bottom like those in abrasional eddy holes of surface streams. Most of them show flutes on their walls, oriented as they should be, and decreasing back from the passage in size and depth of cups as they should, if a stream headed for Roaring River swirled past them after half of each had been destroyed in deepening the passage. In large part, the drilling of these potholes has made the narrow passage.

Another feature of this group of potholes is a consistent asymmetry, the downstream wall nearly vertical, the upstream wall overhanging the deepest place in the pothole. This asymmetry also occurs, with the same relation to direction of former current, in the narrow gallery leading to Wonder's domepit. It is another usable criterion for direction of flow of a vanished cave stream.

A silicified Zaphrentid coral, wholly unworn but almost free from the pothole wall, indicates solutional origin of the "Alley" potholes.

Dozens of continuous bridgings still cross the "Pothole Alley" passage in Mammoth. Natural bridges have been presented in this paper as records of phreatic origin of the chamber. One reservation was made, however. "Trick Falls" natural bridges might be left by high-gradient vadose streams if rock conditions were favorable. Here

[27] Malott, "Lost River at Wesley Chapel Gulf, Orange County, Indiana," *Proc. Ind. Acad. Sci.*, Vol. XLI (1932). This authority, in a personal communication, states that standing water left in the pits during weeks between Lost River floods may contain much organic matter. It is his belief that (1) the holes in Wesley Chapel Gulf Cave are as much the result of solution without current as they are true potholes and that (2) the character of the rock layer is a factor in determining the existence of the pits.

the exception seems to be realized, with the multitude of potholes recording a vigorous flow—a steep descent—during the brief time when vadose detour occurred here from a higher capacious chamber to a considerably lower large gallery.

Numerous long, narrow, little-branched avenues of Mammoth possess flutes and potholes in the lower part of their walls, virtually all showing a westward flow toward Green River. Absence of these features a few feet above the present floor can hardly mean that, though once present, both flutes and potholes have since been destroyed. The walls are smoothly solution marked, not angular from falling-off of rock fragments. It seems much more likely that present depth had been largely attained by the time the stream discovered the route, that these passages are not like Pothole Alley in origin.

SPECIFIC CASES OF SOLUTION WITHOUT CURRENT FLOW

The three items under this heading are related genetically to those listed under "Phreatic Forms and Patterns" but are not strictly either cave forms or patterns.

BOXWORK

Caves in the Black Hills of South Dakota possess a remarkable and perhaps unique feature of wall and ceiling sculpture aptly termed "boxwork." It consists of a reticulated network of thin blades projecting out from walls and down from ceilings, the different blades thus enclosing irregularly shaped and sized spaces—the open boxes which give the feature its name. Not all blades extend laterally far enough to join others, so not all spaces with three or four bounding blades have complete ground-plan enclosure. Straightness and subparallelism of members of two or more systems of blades suggest joint control. Despite a very prevalent incrustation of calcite crystals on the blades, they are not in themselves secondary deposits. Nor are they projections of the native limestone. They have been correctly described as the projection of a calcite-vein network that is widely distributed throughout the Pahasapa limestone of the region.[28] Blocks excavated in widening passages in several of

[28] E. L. Tullis and J. P. Gries, "Black Hills Caves," *Black Hills Engineer*, Vol. XXIV, No. 4. The authors review all earlier interpretations of Black Hills caves and submit a bibliography of thirty titles.

these caves, Wildcat in particular, show clearly that the intricate system of minor veins in the rock is continuous with the intricate pattern of blades on the cave-facing surfaces. Also shown is a reddening and partial disintegration of the limestone in the still-filled boxes just back of these surfaces. Locally, the rock has been altered to a dolomitic sand.

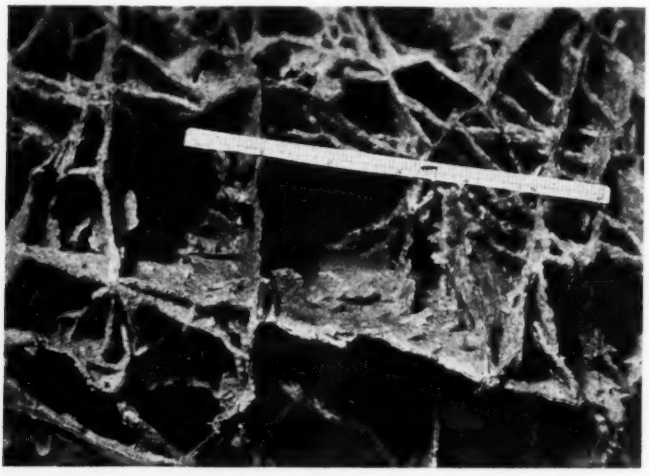


FIG. 27.—Boxwork on walls of Wind Cave, S.D. From Tullis and Gries "Black Hills Caves," *Black Hills Engineer*, Vol. XXIV, No. 4.

The boxwork in places is literally astounding. Entire strata have disappeared from cave walls by receding behind a mask of boxwork. One of Wind Cave's ceilings bears a boxwork record of one definite stratum 3 feet thick, nothing of which remains over an area of several hundred square feet except the skeleton work of the original veinlets.

Despite the thinness of the calcite veins (many are no thicker than a postcard), there seems no escape from the conclusion that, during cave-making, water dissolved the native limestone in preference to vein calcite and left the delicate empty-honeycomb structure in relief. Differential attack therefore was determined by differential

solubility, and the attacking water, up against all boxwork ceilings, had no current adequate to destroy these fragile blades. The incrustations, also testimony to a complete water fill, have subsequently strengthened the box walls, increasing them locally to many times the original thicknesses.

CAVE SOLUTION RELATED TO STYLOLITE SEAMS

The relations of bedding-plane stylolites to caves in the same strata invariably testify to the completion of stylolites before cavern solution ever began. Thus the stylolite seams might be expected to provide cave-making water routes, but this has been recognized only twice in field studies. A contrary procedure has been seen, however, where the stylolite seam was less soluble than the pillar rock. This also occurs in Wind Cave, South Dakota.

A certain flat ceiling happens to be determined by such a bedding plane. Along it, the limestone of the interpenetrating columns has been removed, leaving the striated surface which bounded them hanging down an inch or more as an exceedingly fragile, thin, transparent, convoluted curtain. A breath might wreck it. Recrystallization on the pressure-affected surfaces made that calcite slightly less soluble than the limestone in the columns. Complete phreatic conditions, with a very slow circulation and no later experience with current—either water or air—seems recorded.

SOLUTION OF FALLEN BLOCKS

Wind Cave provides yet another kind of record of the solvent work of phreatic water. It consists of accumulations of fallen roof blocks whose fracture outlines have been destroyed, whose surfaces are marked by pockets eaten into them from all exposed sides, the enlargement of pockets leaving sharp ridges and even spines projecting. The pocketing is identical with that on wall and ceiling rock *in situ* but clearly was made after the blocks fell. Wind Cave has no record of a general-filling episode or of a cave-floor stream. These floors with solution-marked blocks have suffered no modification since the phreatic water was drained off. An equally good example of this kind of record exists in Stage Barn Caverns, another Black Hills cave. In less striking development, many other caves also show it.

Solution of blocks after falling is one way by which large caverns may grow under wholly phreatic conditions. In the exposure of greatly increased surface to ground water, the procedure is akin to the enlarging of a spongework to a final cavern stage. One needs to assume that circulation was adequate to supply unsaturated water for the work. But because of good evidence for lack of current and a total lack of evidence for current, one is barred from thinking of a cave-floor stream or a marked subwater-table flow.

PARTICULAR COMBINATIONS AND SEQUENCES OF PHREATIC AND VADOSE HISTORIES

PENDANTS

Various hanging forms of native limestone on cavern ceilings exist, for which no one method of origin can be argued and no one generic name should be used. The writer wishes to restrict the term "pendant" to those groups of closely spaced, similarly proportioned hanging forms exemplified in Seawra Cave, Pennsylvania, Wonder Cave, Tennessee, and Endless Caverns, Virginia. Though the conditions of pendant origin have not been identical in the three caves, they apparently have been sufficiently similar to justify a generic term.

Pendants of Seawra Cave.—This cave's main chamber has a very striking gabled ceiling, each slope about 50°–55°, one determined by the dip of the bedding, the other by the dip of a strike joint. On each side of the gable, the chamber extends downward as a narrow, inclined slot. There is no structural control to produce a flat ceiling.

But Seawra has one flat-ceilinged room, a big pocket in roof rock off the bedding-controlled inclined slot, lying about 20 feet downdip from the main chamber floor and elongated along the strike. This limestone cavity is largely filled with sand and clay to the ceiling and the air-filled space, though 25 feet wide, is less than a foot high. But one part of it, about 50 feet long, has adequate head room because of a slump pit, down which the upper 8 feet of fill has disappeared. The cone-shaped hollow has been graded to make an even floor for visitors.

The nearly flat ceiling of this room, the "Bridal Chamber," is covered with an anastomosing complex of half-tubes, suggesting the Ste

Genevieve bedding-plane anastomoses, though here the tube-marked plane departs about 50° from the bedding. Tubes are so closely crowded and junctions are so numerous that tube continuity is not very marked in most places. Instead, the ceiling might well be described as covered with numerous short pendants, a few inches to nearly a foot long, these constituting the intratube areas. Whatever conditions determined the tube complex of necessity determined this pendant-marked ceiling.

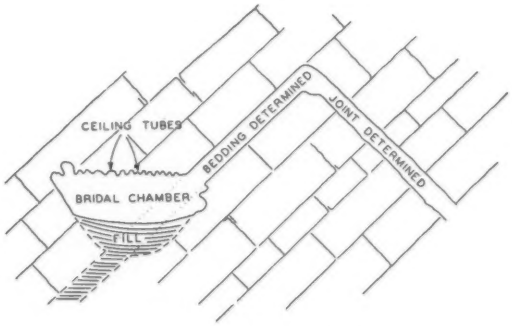


FIG. 28.—Cross section at the Bridal Chamber in Seawra Cave, near Lewistown, Pa.

The genetic conditions are indicated where the fill comes up to the bottom of the pendants at the northeast end of the room. The wide, shallow maze between roof rock and detrital fill is a streamway; the fill is its depositional record, the ceiling its erosional record. This intricately complex channel was being deepened *upward* because accumulating insoluble detritus was raising the stream bed. The flat ceiling, truncating the structure, is a record of the water-level. The stream found the inclined bedding slot already existing, first flowed along it somewhere below the lowest exposure of the fill. Locally it got out, and remained out, of the inclined slot as it upcut. The vertical dimensions of Seawra's Bridal Chamber are due wholly to ceiling solution, caused by constant aggradation of the stream bed. Specific reasons for the labyrinthine complex are not obvious. One would expect pendants with such great exposure to circulating water to be

destroyed, not originated, in such a situation. If upward deepening of the tube anastomosis had ceased at any time while stream flow continued, pendants probably would have wasted away. Only continual addition of sand and clay to the deposit close beneath this flat ceiling could maintain the pendants.

A giant tube, 24–30 inches in diameter, traverses the ceiling maze and is known to extend 40–50 feet along the strike back in the still-filled portion. This big tube has some sharp turns and at least one Y in its course. It does not belong to the previously described category of joint-determined ceiling tubes. If enough tubes of its magnitude had grown in the complex, larger pendant remnants would have been left among them, the smaller ones disappearing as tube diameters demanded larger ones.

In explaining the Ste Genevieve bedding-plane anastomoses, a floor covered with insoluble sediment was needed. Its homologue in the Helderberg limestone of Seawra's Bridal Chamber is the clay and sand fill. But the Ste Genevieve anastomoses rarely leave ceiling pendants as their tubes enlarge because only rarely do the tubes laterally coalesce to form a continuous low, flat chamber beneath them. What correspond to pendants are really pillars.

Seawra's gabled main chamber possesses no record of current during its solution. The interpretation here presented requires that the two upward-converging slots that make the gable be the product of phreatic solution, that the water table then drop below the bottom of the Bridal Chamber, and that a small, free-surface stream then come to flow along one of the slots. This stream brought in insoluble waste, proceeded to fill the chamber but locally got detoured and by upward solutional attack made the flat ceiling, the new chamber being filled as fast as it grew upward. The pendants, though a record of water against the ceiling, date from the vadose episode.

Pendants of Wonder Cave.—The simple, linear chamber which comprises most of this cave lies apparently in the same horizon of the Ste Genevieve limestone throughout the third-of-a-mile of length examined. The ceiling in places is close to the stream surface, rises elsewhere many feet above the water. The floor is of silt, sand, and fine gravel, the depth of fill unknown.

The ceiling form is a broad flat arch, smooth in most places but

locally composed of close-set pendants 3 to even 6 feet in maximum length. In such places, ceiling expanse may be 50 per cent parting space and 50 per cent pendants. Closely associated pendants tend to have uniform lengths, but there are gradations from areas of long pendants across areas of equally thick but blunt and short pendants to areas of smooth ceiling with only narrow slots penetrating up into it.

Where this gradation occurs along the chamber length, the pendants are best developed on higher ceilings. The gradation is most

FIG. 29.—Pendant-covered ceiling area sharply bounded by areas without pendants, Endless Caverns, Va. From Reeds's "Rivers That Flow Underground," *Nat. History*, Vol. XXVIII (1928). Courtesy of American Museum of Natural History.

marked, however, in cross sections, the best and longest pendants along the margins of the broad arch, the central part having only stumpy forms, if any at all.

Wonder Cave's pendants are remnants of blocks bounded by the close-set joints of two systems. Solutional attack along these joints has been from below, by water flowing in an already existing main chamber. Perhaps a fill existed up to the bottoms of the pendants when they were etched out, as in Seawra, though this is not definitely recorded. Either during or after pendant development, the cave became filled with insoluble waste. Later a stream like that of the

present began flowing between the limestone ceiling and the top of the fill. It partially or completely erased pendants in its course. But it needed less width than the filled chamber possessed and thus, during its trenching into the fill, laterally placed pendants on higher ceilings survived, buried in marginal banks of sand and clay which have since wasted away with further deepening by the stream.

Wonder's pendants therefore record conditions of circulation different from those of today. The linear cave was not made by the present stream.

Pendants of Endless Caverns.—Much of this cave's ceilings bear pendant groups which appear to record solution after chamber growth was essentially complete and after a fill in the chamber had mounted to the ceiling. New wall and ceiling forms appear to have been made subsequent to or late in the stage of pendant growth. There is strong suggestion that the making and the destruction of pendants was in part contemporaneous.

A very striking associated feature of these pendants is a sinuous half-tube form winding along the length of the chamber ceiling as a meandering stream channel might wind along a cave's flat floor. Pendants may be abundant right up to the edge of the groove but are either entirely lacking in it or are short, stumpy forms, only in their thickness comparable to pendants outside the groove. Chester A. Reeds[29] has published some excellent photographs showing this relationship, but he attempts no specific explanation. Figure 29 shows a pendant-covered area sharply bounded by ceiling areas without pendants. On the right is a portion of the sinuous ceiling groove whose development has either erased, or prevented development of, the pendants. On the left is a portion of original chamber ceiling, on which pendants never were formed. Figure 30 shows a meander of the upside-down channel cut approximately 3 feet deep *up* in roof rock. The meander became somewhat enlarged as it was deepened upward, leaving a steep, upside-down, slip-off slope, a three-quarter cone hanging from the ceiling.

There are also elongated pendant-like forms on the slip-off slope.

[29] *The Endless Caverns of the Shenandoah Valley* (New Market, Va.: Endless Caverns, Inc., 1925); "Rivers that Flow Underground," *Nat. Hist.*, Vol. XXVIII (1928), pp. 133–46.

They obviously were successively made, abandoned, and then buried as the stream was pushed farther up into the ceiling by the mounting fill. Minimum velocity on the inside of the meander curve appears to have been a requisite condition for their formation—a con-

FIG. 30.—Upside-down meander channel in ceiling, Endless Caverns, Va. From Reeds's *The Endless Caverns of the Shenandoah Valley* (1925). Courtesy of Endless Caverns, Inc.

clusion that follows also from the pendant-and-channel tube pattern in Seawra and the lack or poor development of pendants in the crest of Wonder's arched ceiling.

CONCLUSIONS REGARDING PENDANTS

Pendants are isolated projecting forms in a complex of surrounding connected moats. They are thus the opposite of remnants among close-set ceiling pockets where the holes are isolated by an essentially

continuous rim anastomosis. Even in cases of excessive overlap of ceiling pockets, the distinction is obvious.

Pendants are not known to be duplicated, in reverse, on cave floors. On walls, they occur only beneath overhangs and, whatever the wall slope, have only vertical elongations. Thus in all cases pendants are the consequence of upward penetration of an anastomosing complex of deep sinuous connecting grooves. In some pendant groups, close-set minor jointing has determined location of grooves. Some groups seem to be limited to certain layers as though otherwise unrevealed structural or textural features were in part responsible for their formation.

A rising insoluble bottom to the causal circulation seems a necessary item for their origin. Pendants therefore are believed to be formed during later stages of a filling episode. Current was necessary to bring in the constantly added sand and clay but generally was not strong enough to enlarge favorably oriented grooves more than any others.

The associated much larger upside-down channels and linear ceiling tracts without pendants may be contemporaneous with pendant development or may record the beginning work of the stream which removed the fill.

CRESCENTIC WALL NICHES IN ENDLESS CAVERNS

In addition to the ceiling grooves, the walls of Endless Caverns carry records of a meandering stream subsequent to the making of the main chamber. Because of the great range in their shapes and proportions, the writer has been unable to group them under a more specific name, though "crescentic wall niches" is only suggestive. Some of them could be classified with the Smittle type of incised wall meanders, others are essentially the "horizontal grooves in cave walls" already described. There are variants, however, in Endless which the writer has never seen in any other cave.

A shallowly incised discontinuous groove, horizontally elongated across the face of dipping beds, is the simplest form. Numerous ones, however, are as high as they are long, hence cannot be called "grooves." In some of these, the radius of curvature becomes larger from the top down, as befits a deepening and enlarging meander's

wall scar. But in others the widest part is at the top. Some are empty half-circle indentations. Some are horseshoe-shaped, deeper back in the wall than they are wide. Some have a central remnant of limestone to correspond to the half-cone slip-off slope in Smittle. Some, however, have this projecting remnant hanging down instead of pointing up. And, most difficult to be explained by the hypothesis, some have a complete pillar, the cavity resembling the mold of a half-doughnut. All cross the tilted bedding; few, if any, have joint control. All of them are believed to be records of a stream much narrower than the chamber, winding because of bars, fallen roof blocks, flowstone obstructions, or simply because of low gradient. Some may have been made as the fill rose to put the stream up against the ceiling, others as the fill was carried away.

VADOSE ALTERATION OF PHREATIC PASSAGES IN MARK TWAIN AND CAMERON CAVES

Note has been made (p. 703) of gravel deposits in these caves, introduced during a late vadose episode of cave history. More evidence for this episode is found in solutional enlargement along a few routes, including those that contain the gravel. In both caves it consists of notable widening at a certain level, above and below which the slot form is unaltered. In Mark Twain these widenings are close to the passage tops, in Cameron a high ceiling slot still remains above the widened portion.

In Mark Twain Cave the widening is traceable as a continuous feature northward along Grand Avenue, then westward along another passage, then northward again until it is lost in a flowstone-talus blockade close to the valley wall. Locally the widening is more than 20 feet across. Repeatedly, the sides of the narrow part below the widening have horizontal undercuttings, niches somewhat like those in Smittle Cave though less strikingly incised in the wall and with much longer radii for the curves. They are perhaps better described as unpaired terraces in the lower part of the slot. In one passage far back in the cave and difficult to reach are some half-cone niches of the Smittle type.

That neither the widenings nor the terracings are stratigraphically determined is clear from their absence in walls of intersecting narrow passages in the same strata. The passages with widenings

and terracings have had some experience with ground water which the others have not had. Since no clay remnants occur on the shelves constituting the bottoms of the widenings, the experience postdates the episode of filling. Since most passages show no widened horizon, they must have remained clay filled at this level while the others were being widened.

Since the gravel in Grand Avenue, Mark Twain Cave, lies below the widened horizon and the terraces, and since all three features

FIG. 31.—Grand Avenue and an intersecting narrow slot in Mark Twain Cave, Hannibal, Mo.

record a vadose stream, it follows that the vadose history involved (1) a fairly long time when the stream had little gradient and it widened instead of deepened, and (2) a time when the stream lowered the clay fill too rapidly to give adequate opportunity for widening, only the terraces recording any solutional change and the gravel recording the vigorous current of the vadose stream just before it returned to a wholly outside route.

Since all passages today have lost the clay fill down to the floor-level, its removal must have been contemporaneous with or later than the vadose stream's occupancy. In part, the clay went out by way of the stream, in smaller part it has gone down slump pits into lower, otherwise unknown chambers.

WATER-TABLE AND SUBWATER-TABLE STREAMS

Davis proposed the term "water-table stream" in 1930. He says: "A low-level vadose stream, draining an integrated system of underground passages, [which] has graded its cavernous course to the level of a near-by valley floor stream . . . . will practically coincide with the water table just as a surface stream does [and] . . . . should no longer be called a vadose stream but a water-table stream." The streams described for Smittle, Meramec, Missouri-Onondaga, and Cudjo caves and the Echo River part of Mammoth Cave's stream apparently fit Davis' concept of a water-table stream. He did not utilize this flow in his theory, preferring a slower, deep-seated, truly phreatic circulation for most cave-making.

Swinnerton,[30] two years later, stressed the solutional importance of "lateral flow in the upper zones of the water-table," arguing that in those zones flowed the greatest volume of subterranean water and that, in this water, saturation was farthest from being attained. Differing with Davis, he saw in these zones the chief horizons of cave-making. He specified these streams as vadose, "stressing the behavior of the fluctuating water-table," and apparently thought of them as filling their chambers to the ceiling only in flood time. Both authors dealt with theoretical concepts, neither presenting detailed descriptions of selected examples of their concept.

Gardner,[31] five years after the Davis paper appeared, proposed his theory of "the tapping of static water-zones (by deepening of surface valleys) in the process of base-levelling," believing that "large caverns with their integrated systems, in both the horizontal and the vertical components, originate and develop in thick terranes of limestone above the water-table." Gardner cited the appropriateness, for such origin, of the structural, lithologic, and topographic features of both Mammoth and Carlsbad caves, but his paper contains few specific data on these caves. In more detail he discusses Dry Branch, a sinking creek with a resurgence in Hardin County, Kentucky, where "only in periods of excessive rainfall is the cavern entirely

[30] "Origin of Limestone Caverns," *Bull. Geol. Soc. Amer.*, Vol. XLIII (1932), pp. 663–94.

[31] *Op. cit.*

filled with water," citing it as "typical of the initial stage of cavern growth."

In this section, examination of actual cases of strong flow, past and present, will be made and evaluated with reference to the concept of water-table streams.

LARGE SPRINGS OF MISSOURI

According to O. E. Meinzer,[32] Missouri is surpassed only by Florida in possessing large springs in limestone. Most of them have true spring mouthings, to which the water obviously rises to escape. Few emerge from caverns with air above the water surface, and, in such as do, the ceiling is down to the water a short distance back. Though the low-water discharge of some of these springs drops to less than half of the high-stage discharge, there is no comparable lowering of the water-level in the cavern mouths. Greater velocity, rather than greater depth and width, makes the flood discharge possible. Most of the springs "boil up," the basins of some containing 40–50 feet of water. Nearly all the springs emerge at valley-bottom levels, many of them without any notable re-entrant in the valley slopes or cliffs above them. None of them emerges on a hillside slope.

Courses of the big subterranean discharges upstream from the springs are largely unknown. If the streams are like Echo River, with large air-filled spaces above the water, it is curious that none of the numerous Missouri caves leads down to one of them. A better comparison appears to be with those stretches of Roaring River whose ceilings are submerged during virtually all the year and nearly 50 feet below the free surface of flood time. These Missouri subterranean discharges are not like Lost River, Orange County, Indiana, for in the entire region no streams of comparable magnitude disappear underground. The springs are not resurgences.

Two different concepts of the relation between surface and subterranean drainage in Missouri are at once apparent: (1) the subterranean courses are the older and have been segmented by deepening of surface valleys and (2) valley deepening, by steepening the water-table slope from uplands, has brought about an integration of

[32] "Large Springs in the United States," *U.S. Geol. Surv. Water Supply Paper 557* (1927).

subterranean waterways and has thus made the big spring streams possible. The writer has little desire to argue deductively for either of these concepts. Let us examine some field evidence before reaching a conclusion.

Greer Spring, Oregon County, Missouri, consists of two springs a short distance apart in the bottom of an inner gorge of a steep-sided, youthful tributary of Eleven Point River. The larger spring boils up in the stream bed and nothing can be seen of its conduit walls. Upstream a short distance, the smaller spring discharges from a low cave at the bottom of the gorge wall. Meinzer reports that the maximum discharge of the two is 835 second-feet, three-fourths of which is contributed by the larger, and that even in flood discharge, the water remains clear. The permanent tributary is maintained by the spring alone. The gorge ends a short distance upstream from the springs and the gradient steepens thence into the tributary valley head which carries only storm water.

There is a waterfall ledge about 6 feet high at the upper end of the gorge, a very irregular ledge composed of carious limestone. Immediately upvalley from it, there is no rock floor for a little way, nor any rock walls. Instead, residual earth fills an enlarged cross joint in the valley sides and bottom. This enlargement can be the work only of ground water before the gorge was cut, therefore before the springs existed. Furthermore, the gorge walls overlooking the springs contain numerous tubular openings, some quite irregular, some vertically elongated along joints, some spaced out along bedding planes, and in places all united into an obvious anastomosis.

The inner gorge, therefore, has been cut into an older phreatic spongework, a ground-water route that preceded the open gorge. The springs indicate that the lower main routes are still functioning. The surface tributary valley's deepening has allowed this large ground-water discharge to escape, and deepening of the inner gorge is the work of the greatly augmented flow which this tapping provided.

But why are there two large springs so close together? It would be extraordinary if two large conduits should so develop, whether both drain in from the same side of the valley or flow in opposite directions. It seems more probable that one conduit existed, and

that the two springs are discharges from the severed and now separated ends in the bottom of the gorge. This idea requires a reversal of flow in the portion originally downstream from the gorge intersection. If the idea be correct, then the subterranean stream is not flowing continuously downgrade. Its flow is determined by hydrostatic pressure; it is like a water main which, if ruptured, may discharge from both ends of the break.

FIG. 32.—Abandoned phreatic water routes, Alley Spring State Park, Mo.

Features of all other large springs of Missouri and their environs, known to the writer, fit into the same picture. Alley Spring, Shannon County, discharges from the base of a limestone cliff in which, higher up, several tubular solution cavities, 1–3 feet in diameter, are shown in section. On the east side of the valley, a little below the spring, more than a dozen such abandoned tubes show, some of which have ramifying connections. They are old routes of the earliest, unintegrated ground-water flow, not in any way the product of weathering on the cliff faces. Corroded dripstone forms in them are close to the present valley wall and can be seen from the park trail.

Meramec Spring, Phelps County, has only a narrow upland spur back of the cliff overlooking it and cannot possibly obtain even its

minimum discharge from that area. The entire upland here, bounded on three sides by deep valleys, has no more than 15 square miles whose ground water could drain downgrade to the spring orifice, and all that area is well provided with surface valleys. The spring's maximum measured discharge of 467 second-feet must come from a larger area than this and therefore must cross beneath some drainage divides. From only one direction can it avoid crossing beneath deep valleys as well. Certainly Meramec Spring would not be called the "emergence of a water-table stream" by either Davis or Swinnerton, yet it typifies most of the large subterranean streams of the Ozarks. Since the spring responds promptly to rains and is turbid at flood discharge, the subterranean route must be integrated, well opened, and at no great depth below the water table. The writer believes that if this route could be drained dry, we would find a long, linear gallery closely resembling that of Meramec Cave, Smittle Cave, and Missouri-Onondaga Cave, though lacking the later superimposed modifications that have been described. It would possess pockets and joint-determined wall and ceiling cavities, it would have no fill, for the episode of clay filling is still ahead, waiting for cessation of the big discharge.

Big Spring, Carter County, is another large subterranean stream (589 second-feet maximum discharge) turbulently mounding the water surface in its pool at the base of a limestone cliff. The only visible part of the orifice is the very base of the cliff. Here several openings function, but the mounded pool surface bespeaks a large tubular cavity a little lower, one so full that the upper part of the discharge is crowded up into neighboring small units of the system.

Round Spring, Shannon County, wells up in a nearly circular, vertically walled pool, with no indication of where the water enters it. The pool is said to be 55 feet deep. Discharge from this pool is by way of a wide, low, roofed opening about 75 feet long in the side toward the surface stream which it reaches in about 30 feet of descent. A pillar interrupts this opening. In another place, a good-sized tubular opening shows in the cavity wall, well above the water-level, with corroded dripstone a few feet back in it. The pool basin is an unroofed cave whose bottom is below that of the valley. It is

a collapse sink in everything but the fact that it discharges water upward instead of downward.

Adjoining the Round Spring State Park on the same side of the valley and but little higher above the valley floor is Round Spring Cavern. The entrance route for more than 350 feet is constricted, owing some of its width and height in places to excavation by the cave owner. This narrow route traverses a spongework where one

FIG. 33.—Main discharge at Big Spring, near Van Buren, Mo. Photograph by Paul Herbert.

may crawl through connecting cavities alongside the trail for 50 feet or more. The main cave is much larger and has the general proportions of Meramec, Smittle, or Missouri-Onondaga caves. Followed in either direction from the junction of the entrance route, one encounters a complete blockade of the capacious linear chamber by a pile of fallen debris, cemented by flowstone. One of these is known to have a sink hole above it.

The little stream in Round Spring Cavern enters the spacious chamber by a bedding-plane leakage, follows only a part of this chamber's length, and then leaves by a similar bedding-plane route to appear as a small spring at the base of the valley wall. Very clear-

ly, this stream did not make the cave. The stream that did has been detoured to other routes, perhaps by the blockade dams, more probably by discovery of lower possible escape, and in all likelihood is now emerging as Round Spring. For some distance back from the pool, it must be in a truly phreatic passage, well below the lowest water table of the year. It should at present be making another long, capacious, tubular chamber out of selected routes in an older spongework.

By implication, both the Davis and the Swinnerton water-table streams must have air above them during most of the year. By both authorities the direction of subterranean flow is essentially that of surface flow, the water-table gradient from uplands to major valleys determining it. By Davis, the water-table stream must be a graded course, though continuous downcutting of one route is not so likely as segmentation, or vertical piracy, in attainment of grade. Exceedingly high ceilings are thus avoided. By Swinnerton, water-table streams are the chief cave-makers. By Davis, they are unimportant successors to the phreatic cave-making flow.

The Missouri big springs, the dominant visible feature of subterranean drainage in the Ozarks, are all discharges from below the water table. They must have long integrated underground routes whose cross-sectional areas might well compare with those of the several caves repeatedly named. They are the result of "lateral flow in the upper zones of the water-table," but this flow is below the lowest drought levels of that table. These underground routes are older than the present topography, they fail to conform to its lineaments,[33] and they are now being segmented as river valleys are deepened. The named caves have already been drained by water-table lowering, though they are collecting enough vadose water to maintain the small streams that today are modifying them.

Segmentation of these main subterranean routes through the deepening of surface valleys provides more prompt escape from the confines of a subterranean course and may well produce a greater discharge. This in turn may aid in development of the main tubes of

[33] Josiah Bridge, in "Geology of Eminence and Cardareva Quadrangles," *Mo. Bur. Geol. and Mines*, Vol. XXIV (1930), says: "The subterranean drainage is independent of the surface divides and is controlled by the major structural features of the region."

the system. But again it must be urged that the field evidence indicates tube-full flow up to the episode of clay filling that so commonly occurred before vadose stream work began.

An ideal record of segmentation of the phreatic water-main type of cave would be two abandoned tubular gallery caves, well up in the opposite slopes of a deep valley and aligned with each other. Here one could well believe that a continuous cave had been cut in two. Such a setup may exist at Highland Cave, Arkansas, which is about a hundred feet above the narrow valley floor, which essentially perforates the divide it is in and which is reported to have a homologue in the opposite valley wall. Highland Cave is a great tube of the right character for this interpretation but, since the other cave was not investigated, positive statement here is unwarranted.

Davis also suggested the term "subwater-table stream," apparently having the Floridian terrestrial and submarine springs in mind. To the writer this term perfectly describes the Missouri big spring flows. It equally well describes the causal mechanism for the many caves recording a strong, unidirectional, phreatic flow which succeeded an episode of multidirectional spongework- and network-making. Abandoned as valley trenching proceeds, the old routes may, like Mushroom Cave in Meramec State Forest, Missouri, and Cathedral Cave near Leasburg, Missouri, now mouth high on the valley slopes.

Subwater-table streams, the result of integration and concentration of drainage somewhat below the water table of droughts, have been the chief agents of cave-making in the Ozarks. Meramec, Missouri-Onondaga, and Smittle caves belong in the same group with Cathedral, Highland, Mushroom, and Round Spring caves. In Mammoth Cave, subwater-table streams have made those large chamber routes typified by Audubon, Broadway, Cleveland, Gothic, "New Discovery" of 1938, and Silliman avenues. Indian and Wonder caves in Tennessee are of this genesis. Cave-in-Rock, Illinois, is a short but well-shown tube of this origin, much of it still filled to the roof, much destroyed by Ohio River's valley-making. Sparks Avenue, in Mammoth, also belonging to this category, has special features that need special attention.

Sparks Avenue leads from River Hall, a part of the Echo–Roar-

ing–Styx river complex rarely flooded by backwater, toward Mammoth Domes. En route, Sylvan Avenue branches off at a low angle and farther along Sylvan itself has a divergent passage. Rock floor is obvious in places. The passages are rudely tubular, with wall, ceiling, and even floor cavities where crossed by joints. The relations are truly divergences, the direction of flow amply attested by

FIG. 34.—Cave-in-Rock, Hardin County, Ill. Weathering has broken away much of the tube's rock floor at the entrance. Farther back in the cave, the tube shape is nearly intact. It seems impossible that a free-surface stream could have made this concave floor. Photograph by G. S. Monk.

thousands of flutes on walls and on ceilings. In this direction there is a small upgrade to both Sparks and Sylvan.

Based on this same evidence of flutes, the system also had a converging conduit, entering Sparks from the general direction of River Hall but beginning in a complex of untraversable waterways imperfectly integrated from bedding-plane tubes. Downstream, collapse blockades prevent further exploration in all members of the group.

Surely we must consider this former vigorous discharge through the Sparks Avenue system as phreatic, for the chambers were of necessity completely filled with water at any stage of flow. But there is also good evidence that this flow did not give origin to the cham-

bers, that they date back to still earlier phreatic conditions. It is found in the relations of ceiling flutes to ceiling joint-determined cavities.

In the ceiling of Sparks these cavities cross the chamber length at various angles. They are deep, narrow, somewhat boat-shaped. Excellent flutes occur on the downstream sides of these cavities, recording the *upward* flow of an eddy in them. The flutes become more weakly expressed farther up in the cavity but enough exist on the opposite side—the upstream side—to record definite downward flow as the eddy current returned to the main. Where the ceiling cavity

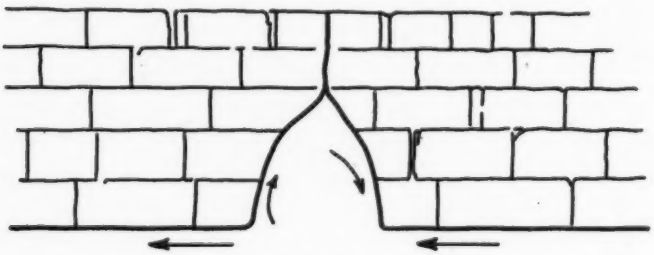


FIG. 35.—Ceiling profile in Sparks Avenue, Mammoth Cave, Ky.

crosses the main chamber diagonally, a diagonal component to the two directions of eddy flow is recorded.

There are no flutes in the pointed arch apices of the cavities. Insufficient eddy vigor in this constricted space is thus recorded, and the priority of ceiling cavities to flute development becomes clearly established. Sylvan and Sparks avenues, and other similar ceiling-fluted chambers in Mammoth, are therefore interpreted as phreatic passageways, during whose earlier history there was no vigorous flow but which suffered a later and relatively brief phreatic experience with a strong current under hydrostatic pressure. This later flow was the subwater-table stream, here using an inherited anastomosis to the end of its history.

CAVES IN TILTED FORMATIONS

Since most limestone formations are essentially flat-lying, the water table in them so nearly parallels the stratification that one

cannot be sure to which of them any horizontal extent of a cave system is due. Inclined formations should give a definite answer. Davis, clearly recognizing this, deplored the paucity of literature he found on caves in inclined formations. What he did find was that some Shenandoah Valley caves, in folded rocks, possess notable horizontal extent. This suggests "a control of solution by the former water-table," and these caverns become "of particular importance because they do not support the main thesis of this essay as to the solutional excavations of caves by ground water below the water-table in the first epoch of their history."

Within two years of publication of Davis' paper, R. W. Stone brought out a new edition of his bulletin on Pennsylvania caves,[34] most of them in folded rocks, and stated that "it is the writer's belief that many and perhaps most of Pennsylvania caves were excavated by solution beneath the ground-water table and that subsequently they have been drained, filled with air in place of water, and so their history is divided into at least two distinct cycles." Stone cited a number of features as evidence of phreatic origin[35] but said nothing about the relations of cavern-system planes to bedding planes.

CHAMBERS EXTENDED ALONG THE DIP

The writer has studied eight Pennsylvania caves in definitely tilted rocks, nine Virginia caves so located, seven such in the Black Hills, and one each in Illinois and Colorado, looking for records of significant relations between water-table planes and bedding planes. Five of these twenty-six caves are almost precisely what Davis was hoping to find described: networks or spongeworks developed in dipping strata to resemble the empty stopes of room-and-pillar mining in inclined coal seams. One of these, Cudjo's Cave, has already been described, and evidence has been submitted to show that the spongework chambers antedate the tubelike alterations made by the

[34] "Pennsylvania Caves," *Penn. Geol. Surv. Bull. G3* (4th ser., 1932).

[35] With the following criteria which Stone cites, the writer is in complete agreement: inverted pits in ceilings, the size and shape of a nail keg or barrel; long, narrow points and slabs pendant from the ceiling or projecting from the walls; projecting ledges of soft, shaley layers; small wall chambers connected with main gallery only by a hole high above floor of lesser cavity; dead-end passages; incongruous variations in sizes of chambers now in use by a given cave stream.

cave stream of today and that a filling episode must have intervened. The cave stream's successively lower courses along the strike are a record of lowering water table, itself consequent on deepening of outside valleys. Hence the original Cudjo's Cave was a phreatic spongework developed well below the original water table, just as Davis asked for.

Battlefield–Crystal Cave, Virginia, is the only Shenandoah Valley cave known to the writer in which chambers extend down the dip, here about 12°. They are due to enlargement of joint cracks, hence the cave is an inclined network rather than a spongework. There are two major joint sets at right angles, the dip of the bedding bisecting two of these four angles. The cave contains no record of vadose water work.

Hipple Cave, Pennsylvania, lies in a low ridge between two broad-floored valleys. A stream follows most of the cave length, rising as a spring near the entrance, flowing along the strike and leaving by a low-roofed exit into the valley on the northwest. Daylight can be seen near the exit but the route is untraversable. It is very probable that the stream water comes from the valley on the southeast side. Because of heavy secondary deposits of dripstone and flowstone, Hipple's plan is not so obvious as that of Battlefield-Crystal, but it is essentially the same. The two joint sets here parallel the dip (28°) and the strike, and the intersections determine the location of the cave's more capacious chambers. There are many fine ceiling pockets and wall pockets in these chambers. Theoretically, the open-cave system was once much more extensive than now. It should extend downdip, below present water table, though now filled with clay. It once extended updip above the present ridge top. One may scramble up the bedding incline along a dip-joint chamber until close to the top of the ridge. Heavy flowstone, dripstone, and cemented collapse blocks constitute the roof today. The present stream is doing little, and has done little, to modify the inclined phreatic network.

Cave of the Winds, Colorado, has three fairly definite "levels" (though each is inclined), the chambers being well-widened strike- and dip-joints. The entire system lies near the middle of the Manitou limestone, about 200 feet of which is exposed in the vertical walls

of Williams Canyon, with a dip of 10°–15° away from the mountains. Most chambers follow dip-joints, but the more capacious ones are compounded of one strike-joint passage and a series of dip-joint openings. Much enlargement has occurred at the intersections and in one case of sixteen connected dip-joint rooms, some are essentially only wall cavities, hardly more than three times as long as they are wide or high. Others of this group are main passageways of the cave system.

Cave of the Winds is an ideal phreatic inclined network within its vertical range of 30 feet. No chambers are high, bedrock floors separate the different levels, windows through these floors connect them. In perfect harmony with this three-dimensional network pattern are the wall and ceiling sculptures. Excellent pockets have been dissolved back in them, usually about as deep as wide, although the ceiling pockets are the deeper. Some pockets have suffered so much enlargement that only irregular bladelike and spikelike projections remain. Nothing seen in this cave indicates that a free-surface stream has ever used any of its chambers.

Cave Hill Cave's (Illinois) entrance is 200 feet or so above the base of a north-facing, 600-foot, fault-line scarp of Chester formations, a scarp that overlooks miles of low flat country on down-dropped Pennsylvanian shales. Entrance is through a small, shallow collapse sinkhole, thence by a descent of 20–30 feet over an insloping talus deposited in the cave, the debris spilling back down into three intersecting cave passages. The ground plan is a network of passages along three, possibly four, joint sets, dominant among which are the two that approximately parallel the dip (10°–15°) and strike of the Kinkaid limestone. The open-cave system is narrowest in dip direction, only three or four closely spaced open strike-joint passages existing. But the dip-joint passages almost undoubtedly continue down below the clay floor that now terminates their open portions. In other words, the cave is still largely filled with clay and its elongation along the strike is only that of the air-filled upper edge of the system. Had the dip been toward the escarpment's face, instead of back into the hill, much more of this system would now be enterable.

All passages are narrow aisles, widest close to the ceilings but so

narrow in the lower part, particularly in the eastern end of the cave, that traverse must be made, as in Pokerville Cave, by straddling or bracing across the slots. Unlike Pokerville, however, the slots are parts of the original galleries. Since all passages share in the upper widening, it probably records greater solubility of strata at this horizon. It is a phreatic trait. Indeed, Cave Hill Cave is still nearly 100 per cent phreatic in origin.

Dip-joint passages are terminated upgrade by talus and fallen ceiling blocks, but many cases of fibrous root tips in these termini show that the hillside slope is just above and that it transects the

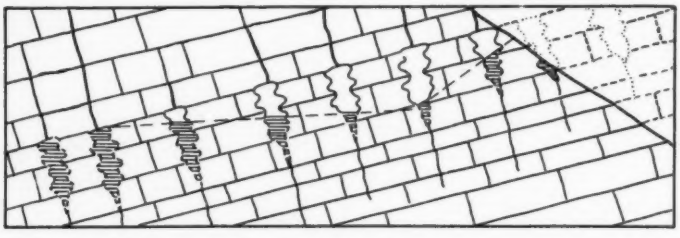


FIG. 36.—Diagrammatic dip section across the open strike passages of Cave Hill Cave, to show theoretical continuation downdip below the surface of the fill and updip beyond present face of escarpment.

original cave system. Comparison with Mark Twain Cave in this respect is very close.

Where passages are especially close set, widening has left rows of huge, thick pillars of steep pyramidal form, some of them now completely cut off from contact with the ceiling. This part of the cave is in that intermediate stage between the beginning of a joint-determined network and the completion of a large chamber. Because the strike joints are perpendicular to the bedding the pillars all lean about 75°–80° in a common direction. Some pillars, cut off at the bottom by vadose seepage water now entering from the hillside, have toppled over against others.

Cave Hill Cave was made before the broad flat Saline River lowlands to the north and the broad synclinal valley to the south had been eroded. At least 1,500 feet of rock has been removed from above the Kinkaid limestone, and the cave dates back to the time

of that removal. Much of the original cave is now clay filled, much has been destroyed by scarp retreat. No subwater-table stream is recorded in the cave, nor any water-table stream. It is interpreted as the product of that slow, deep ground-water circulation which Davis visualized.

CHAMBERS ALONG THE STRIKE

Among extended linear caves which occur in tilted formations, more chambers are known with horizontal elongation than with extension down the dip. As already noted, though Davis found no descriptions in the literature of dip-elongated chambers, he found and was puzzled by descriptions of two Shenandoah Valley caves in inclined beds, Endless and Luray, whose chambers were chiefly horizontal. Based on field study of fifteen caves, this type of chamber will now be discussed. Horizontal elongation does not imply bedding-strike chambers alone. Nearly half of the fifteen caves studied show horizontal elongation along the strike of joints, chamber location being largely indifferent to orientation of the bedding.

In the following catalogues, let it be understood that some of the phreatic traits earlier discussed are to be found in every cave listed and that only one of these caves has an adequate record of later vadose or water-table stream work. Furthermore, listing of a cave in any one of these groups does not imply that all its chambers are of the same origin.[36]

1. Horizontal chambers along bedding strike, without reference to strike joints
   - Dixie Caverns, Virginia
   - Grand Caverns, Virginia
   - Massanutten Caverns, Virginia
   - Wonderland Caverns, Pennsylvania
2. Horizontal chambers along intersections of strike joints and bedding planes
   - Luray Caverns, Virginia
   - Historic Indian Cave, Pennsylvania
   - Seawra Cave, Pennsylvania
   - Crystal Cave, Pennsylvania

[36] Endless Caverns, cited by Davis, has not been listed because most of its horizontal passages seem to show but little control by either bedding or jointing. But since it has considerably greater linear extent across the strike than with it, and, in its 2,000 feet of length, the main continuous portion has less than 100 feet of vertical range, Davis was justified in his concern.

Lost Cave, Pennsylvania
Baker Caverns, Pennsylvania (nearly vertical beds, nearly horizontal joints)
Cave of the Winds, Colorado
Cave Hill Cave, Illinois

3. Horizontal chambers along joints approximately parallel to direction of bedding dip
Grand Caverns (a few chambers)
Massanutten Caverns (a few short chambers)
Virginia Caverns
Shenandoah Caverns, Virginia

The writer's explanation for the marked horizontality of passages in tilted formations is built largely on the concept of subwater-table stream modification of older phreatic three-dimensional, inclined networks or spongeworks, the deeper portions of which are now filled with clay, only the upper edge of the system being exposed. Though not all chambers of this category can be so explained and some caves in the above lists may never have carried such streams, the evidence seems good that many of the caves have had this sequence. The procedure is well shown in some caves in flat-lying beds, notably Ohio Caverns (West Liberty, Ohio), Mark Twain, Cameron, and Niagara, where free-surface streams have enlarged certain of the slots of a phreatic network.

Many earlier discussed phreatic traits of wall and ceiling sculpture indicate solution of strike chambers beneath the water table. Conduit-like connections between larger irregular rooms (several caves) and conduits through networks and spongeworks of irregular cavities (far end of Virginia Caverns, in particular) seem to require direct current flow for their growth after rooms, networks, and spongeworks were made.

Widening of conduits in the strike has locally produced a curious cross-sectional shape. The widening has been projected far downdip as a low-ceilinged slot, a lateral extension of the main course made by water flowing along the strike, not the dip. In such a very wide, very low, marginal extension of one of Luray's chambers, several island-like squat pillars still survive. This type of cross section seems impossible by any vadose or water-table stream.

The almost total absence of solutional records of free-surface

streams, previously discussed, is significant. Where present, as in Endless and Seawra, the relations clearly indicate an earlier, subwater-table origin of the cave itself and the later impress of these markings in a vadose experience.

Integration of networks to new needs has not commonly yielded the simple type of subwater-table tube cavern. Instead, this later, stronger phreatic flow appears in many cases to have maintained a horizontal anastomosis, at least for part of its route.

If we visualize the caves of this category as originally tabular networks or spongeworks along the dipping formation, we must accept the two assumptions made in the interpretation of Cave Hill Cave. One is that the deeper part of the system, unaffected by later subwater-table streams, still lies buried in clay below present valley-bottom levels. Wet, muddy, and constricted lower openings below the main chamber of Massanutten, Endless, and Wonderland suggest this, but in large measure the assumption can never have supporting field evidence.

The other assumption is that the system once extended up the dip above present land surfaces. If correct, some roofs of these caves should be interrupted by sinkholes or cemented block aggregates where connections existed with the vanished upper part. Several showings of these features are known and probably more exist under heavy dripstone camouflage. But since cave-roof sinkholes and masses of collapsed blocks may be formed under other conditions than those argued for, this assumption also can never be raised to the rank of a direct inference.

The writer believes that addition of the concept of later subwater-table streams, using portions of a Davisian phreatic network or spongework cave system, meets the difficulty which Davis encountered.

THE RELATIONS BETWEEN CAVERNS AND SINKS IN THE MAMMOTH CAVE REGION

Most of the large caverns of this region occur beneath ridges dissected out of the Mammoth Cave plateau. This plateau stands about 300 feet above a lower and much less dissected surface to the southeastward, the Pennyroyal plateau. The two are separated by the Dripping Springs escarpment whose retreat downdip (northwest-

ward) has left the lower surface with outlier hills or "knobs" of the Mammoth Cave plateau formations. These formations are the Ste Genevieve limestone, the Renault–Paint Creek limestone, and, capping most of the plateau ridges, the Cypress sandstone. Remnants of younger formations overlie this sandstone in places but the Cypress, 40–60 feet thick, is the resistant cap rock which has preserved

FIG. 37.—Cross section of part of Mammoth Cave and Pennyroyal plateaus, Ky.

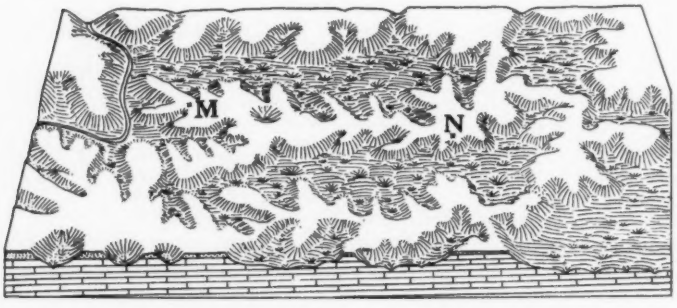


FIG. 38.—The Mammoth Cave district. From Davis' "Origin of Limestone Caverns."

the plateau ridges.[37] Dip of these formations is 30–50 feet per mile toward the northwest.

From 4 to 8 miles westward and northward from the escarpment, the canyon of Green River is cut 300–400 feet deep in the Mammoth Cave plateau, 100–200 feet lower than the surface of the Pennyroyal plateau at the escarpment base. This lower plateau's drainage is accomplished by thousands of sinkholes and dozens of sinking creeks, the water thence going under the higher Mammoth Cave plateau to the Green River trench. Echo–Roaring–Styx river is a

[37] S. N. Dicken, "A Kentucky Solution Cuesta," *Jour. Geol.*, Vol. XLIII (1935), pp. 539–44.

Colossal Cave
Cave
Cave

part of this subterranean drainage,[38] the stream in Hidden River Cave at Horse Cave is a part and Pike Spring near the base of the cliff near Floyd Collins Crystal Cave is a part. Undoubtedly numerous caves of the higher plateau have carried earlier drainage to an earlier Green River trench. But it must be noted that in the northeastern part of the region, neither the abandoned nor the present drainage routes follow the dip very closely; in places they more nearly approximate the strike.

FIG. 40.—Hanging mouth of uvala near Mammoth Cave, Ky. A 90-foot cliff, facing observer but hidden by willows on far edge of terrace, descends from oak-covered slopes to Green River. Photograph by National Park Service.

The 1/62,500 Mammoth Cave quadrangle topographic map and the 1/31,680 Proposed Mammoth Cave National Park topographic map show four major tributary valleys with a dendritic pattern of subtributaries, leading northwestward across the higher part of the plateau to Green River. They are not occupied by streams, they are linear assemblages of sinks resembling stream valleys in ground plan. They doubtless started as surface-drainage ways on the sandstone cap rock, and found subterranean outlet after the sandstone was cut through and the limestone reached. Under the ridges that

[38] Thunderstorm downpours on the Pennyroyal plateau are reported to produce floods in Roaring River some 24–30 hours later.

separate the Doyle, Hamilton, Houchins, and Woolsey uvala valleys lie almost all the known caverns of the region. The problem attacked here is the relation of caverns to sinks. Have the two grown simultaneously or has the development of one preceded and in part determined that of the other?

Longitudinal profiles of these uvalas consistently possess two steep slopes. One is at the head, a clifflike descent from the broad ridge tops and identical with all margins of the hollow. It is an expression of Cypress resistance to erosion. The other is at the mouth, a clifflike descent into Green River Canyon over limestone, therefore not determined by resistance of rock. Between head and mouth, the

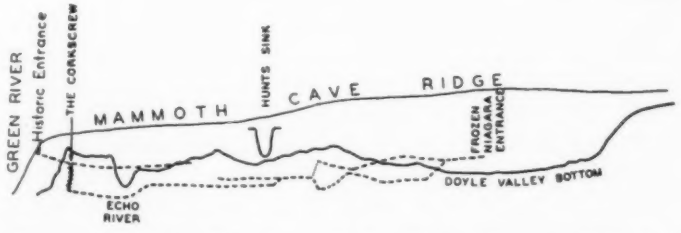


FIG. 41.—Projected profiles of Mammoth Cave ridge, cavern passages beneath the ridge and bottom of Doyle uvala.

profile takes account of many sinks and separating ridges, of varying depths and heights but in general with lower sink bottoms near the river. In Doyle Valley the longitudinal profile shows only two cross ridges as high as the hanging mouth (230 feet above the river) and the deepest sink to reach within 50 feet of river level.

Cross sections reveal another peculiarity. Most of the cross-sectional area of Doyle Valley, for example, is more than twice that of Green River Canyon, despite the greater depth of the master-valley.

Another striking feature, revealed by the topographic map, is the narrowing of each uvala near the river. It is another expression of Cypress sandstone's resistance, for these riverward narrowings are down but little into the limestone.

Clearly most of the waste in excavating these valleys has gone underground, and almost as clearly the subterranean route did not follow the narrow lower course of the surface valley. Projected longi-

tudinal profiles of Doyle Valley and the main Mammoth Cave chambers show that most of the cave, beneath the adjacent ridge, is lower than the bottom of the valley. Did the waste go to Green River by way of Mammoth Cave routes?

Some of the ravine tributaries which determine the dendritic ground plan of the uvalas are a mile long. Most of the longer ones have a sink or a row of sinks, of no great depth, in their bottoms. In some, the very head of the ravine has a sink bottom. Four of the entrances to Mammoth now in use are located in such tributaries to Doyle Valley. If the valley is a great compound sink in itself, developed from a former surface stream course, may not these dendritically oriented ravine tributaries be of the same origin?

The occurrence of Mammoth Cave in the ridge and the close correspondence in elongation of both can hardly be coincidence. The 1938 "New Discovery" chamber also lies under a ridge and elongated with it. It is in Jim Lee Ridge, a big spur off the main ridge. Dry caves should be in ridges, of course, and not below uvala bottoms, but why should they so closely parallel ridge elongations?

We have raised several questions thus far, without answering them. So far as the facts submitted go, opinion might still be divided on the larger problem of simultaneous or sequential development of the caverns and the sinks. The writer believes that more field data, now to be submitted, allow only one answer.

The data come from sinks on the tops of the ridges, not a part of the uvalas, sinks whose bottoms are hardly in the limestone, sinks walled only with sandstone. Though few and necessarily small, they cannot be explained as solution sinks. There must have existed beneath the site of each of them a sufficiently capacious cavern to receive the sandstone which has disappeared. Once this point is accepted for sinks only in sandstone, it must be accepted for the larger and deeper ones in the ridge tops, unconnected with uvalas, which, though extending down into the limestone, are still surrounded by a complete sandstone rim.

The 1/31,680 topographic map shows nearly twenty of these sinks in the broad ridge tops, therefore surrounded by sandstone. Three will be examined. For one of them there is no need for inference; it *is* a collapsed portion of a cave.

This sink is 55 feet deep, steep-sided, barely if at all through the Cypress sandstone. From its bottom, the large Salts Cave can be entered. The sink is somewhat elongated, and one may go underground from either end. The chamber entered from the north end, by descending over a rubble of broken rock for perhaps 30 feet more, has the same orientation as the sink and can be followed northwestward for more than a mile to an exit in the sharply incised Three Sisters Hollow. Salts Cave has suffered so much rock fall that solutional outlines on walls or ceilings are rare. It is reported to be a Mammoth Cave labyrinthine complex of chambers and to connect with the complex known in Floyd Collins Crystal Cave. Under the same upland (between Houchins and Hamilton uvalas) also occur the large Great Onyx and Colossal caves. The relations here are as in Mammoth Cave Ridge, except that the upland is much broader in proportion to its length.

The sink at Salts Cave mouth, therefore, was formed long after the cavern was made, never has conducted cave-making water down into the limestone.

The other two sinks to be examined are Hunt's and Double Cellars, both very close to the northern margin of the Mammoth Cave Ridge, both steep-walled, both more than 100 feet deep, and each one close to the head and in line with a ravine tributary to Houchins uvala. When the very narrow ridge still separating each from its adjacent tributary head disappears, these sinks will become the cliffed heads of the ravine. This is part of the mechanism of uvala tributary growth in these larger ridges. For it to occur, caverns must exist beneath to receive the collapse of the sandstone cover when the sink was initiated. After that, solutional enlargement may occur in the exposed limestone and the ponor may develop into a doline and eventually become part of the uvala.

Instructive is the drainage pattern of Running Branch, a short, high-gradient tributary of Green River a mile west of the Historic Entrance to Mammoth Cave. In a drainage area of $1\frac{1}{2}$ square miles, more than thirty individual temporary waterways are depicted by the contours, converging in typical dendritic fashion and all on the Cypress sandstone. But the water of two-thirds of these shallow valleys never reaches the main, being detoured down seven separate

sinks (two of them compound) that have developed beneath them. Four of the sinks are more than 50 feet deep, the bottom of one is 90 feet below its lowest rim. All are rimmed with sandstone, and the bottoms of the three smallest hardly reach the limestone. Subterranean piracy has detoured nearly half of the Branch's runoff to underground routes, has done it through a floor of sandstone, and

FIG. 42.—Map of Running Branch, near Mammoth Cave, Ky. Part of topographic map of Proposed Mammoth Cave National Park, United States Geological Survey.

does not return it anywhere in the lower course of the main stream. Most of the streams of the vicinity show no subterranean piracy. There must be a particular reason why Running Branch has suffered this exceptional experience.

The reason is found in the cave in the lower valley of Running Branch. It is a vadose-modified phreatic chamber, though carrying no water from the sinks. Some splendid swinging meander arcs are cut in the walls of the older chamber. The top of the cave fill is 25 feet below the bouldery bed of the near-by Branch; thus the cave

has never carried water to the surface stream. Nor has it yet ever received water from Running Branch.

It seems clear that a cave system must exist beneath the Running Branch drainage area and that collapse has formed the sinks which now segment the drainage tree. From the evidence of the enterable cave, that system is phreatic, just as is most of Mammoth.

Not all the queries raised in this section of the paper have been answered. Some will be taken up later. But it is confidently concluded that the ponor and doline sinks in the ridge tops of the Mammoth Cave plateau are younger than the caves beneath. Their water has had almost nothing to do with cave-making. The uvala sinks which separate the ridges are younger than the subwater-table chambers in the ridges, may be contemporaneous with some passages whose walls are fluted, potholed, and meander-incised.

THE RELATIONS OF CAVERNS TO SPRINGS IN THE MAMMOTH CAVE REGION

There are three large concentrations of ground-water discharge to Green River in the region, all at the bottom of the canyon, all rock-roofed down to the lowest levels ever observed, and all on the eastern or updip side of the river. The largest is Pike Spring, $6\frac{1}{2}$ miles by river upstream from Mammoth's Historic Entrance. Another is at the foot of the bluff containing this entrance, and the third is half a mile farther downstream. These latter two are considered the discharges of River Styx and Echo River from the cave. At Pike Spring also, a cave occurs close by in the bluff but, so far as known, it has no stream comparable to the spring's discharge. The Echo River spring is 1,000 feet from the river canyon wall in the bottom of a tributary valley, the other two have full-height bluffs back of them.

Though these ground-water discharge places are called "springs," not one of them appears to deserve the term. Floods in Green River have been observed to reverse the flow of Pike. At the River Styx discharge, a rising Green River sometimes reverses the flow, muddy water from the outside flowing back under the hill into the cave and reappearing at the surface in a few hours as a notably augmented and now muddy discharge from the Echo exit.

It seems to the writer that this detouring of muddy Green River water out of a surface valley, back under a hill and into that irregular complex of connected water bodies (Lethe, Styx, Echo, Roaring) where low-water depths of 40 feet exist, is impossible in any conceivable vadose cave system. It must be granted as very improbable.

Some years ago the Louisville Gas and Electric Company considered constructing a dam across Green River Canyon about a mile above Mammoth's Historic Entrance. Their engineers studied the present courses of ground water by introducing sodium fluorescein into sinks and cave streams of the region. They were "astounded"[39] to find that the dye moved from four different places of introduction in Colossal Cave northward to Pike Spring. Ground-water flow was thus shown to be away from the near-by Houchins uvala, toward and beneath and completely across a broad divide to an exit 5 miles farther up Green River than the uvala's hanging mouth, and only 6 feet lower than the lowest point of dye introductions in Colossal. Dye introduced in a surface sink half a mile west of Colossal Cave moved southwestward, crossed under the uvala bottom, then crossed under the Mammoth Cave Ridge to emerge in Echo River "spring." There is no rhyme or reason for either of these in the present topography. The flow may be vadose today, but in crossing beneath divides and uvala bottoms, at right angles to their elongations, it must follow routes that vadose water never could have established. The cave system is older than the topography above it, is older than the dissection of the plateau.

Because of this and many other known cases of ground-water flow independent of existing ground-water divides, the writer sees in the mechanism proposed by Roger Rhoades and M. N. Sinacori[40] only a theoretical picture. Most cave-making has preceded hill-making and if there be any cause-and-effect relations, they are far more likely to be the reverse of the sequence argued for by these two men.

[39] R. B. Anderson, "Investigation of a Proposed Dam Site in the Vicinity of Mammoth Cave, Kentucky." Manuscript in possession of Louisville Gas and Electric Company. Dated 1925. Existence of this report was called to the writer's attention by Dr. Swinnerton.

[40] "Pattern of Ground-Water Flow and Solution," *Jour. Geol.*, Vol. XLIX (1941), pp. 785–94.

CAVES WEST OF GREEN RIVER, MAMMOTH CAVE NATIONAL PARK

Gardner[41] derived the large, long chambers of Mammoth Cave by downdip movement of vadose water along more porous zones toward and into Green River Canyon. Large caves thus would be limited to the updip (southeast) side of the river, and the vertical succession of chambers would be, as Weller[42] also thought, a record of the lowering water table as the river deepened.

The cave in Running Branch, already noted, is on the downdip (northwest) side of Green River and, to the writer, definitely is not vadose in origin. But it may not meet the needs of the argument since its chamber is small. Another cave on this side of the river will be described—one in which the phreatic and vadose episodes can be clearly differentiated. It is Bat Cave, in the ridge inside the striking Turnhole Bend incised meander of Green River.

The entrance to Bat Cave is about 100 feet above the river in the face of the cliff on the west side of the ridge. It lies between the southern two of three short ravines and is about 150 feet below the base of the Cypress sandstone on the hilltop. Though there are solutional openings in the rock here, the cave itself lies 60 feet lower and is reached by descending over ledges and an inside talus slope close to the cliff face.

The cave is mostly one sinuous linear chamber with a few domepits. Ninety-degree turns are common and there is one 180° bend. The general trend of the chamber is northeast and at the far end reached, vadose water enters down a domepit in which a 2-foot boulder of sandstone is lodged, about 200 feet down in the limestone. Sandstone gravel lies here on the floor, and it is probable that the domepit is beneath the sink shown just east of a house site on the abandoned road along the ridge crest.

This vadose water is hardly the stream with which to make the linear chamber for, shortly after entering, it leaves the chamber, almost by filtering out. Either it re-enters or another vadose trickle enters nearer the entrance, falling from a small hole in the wall, but this water soon disappears down a narrow, debris-filled slot in the

[41] *Op. cit.* [42] *Op. cit.*

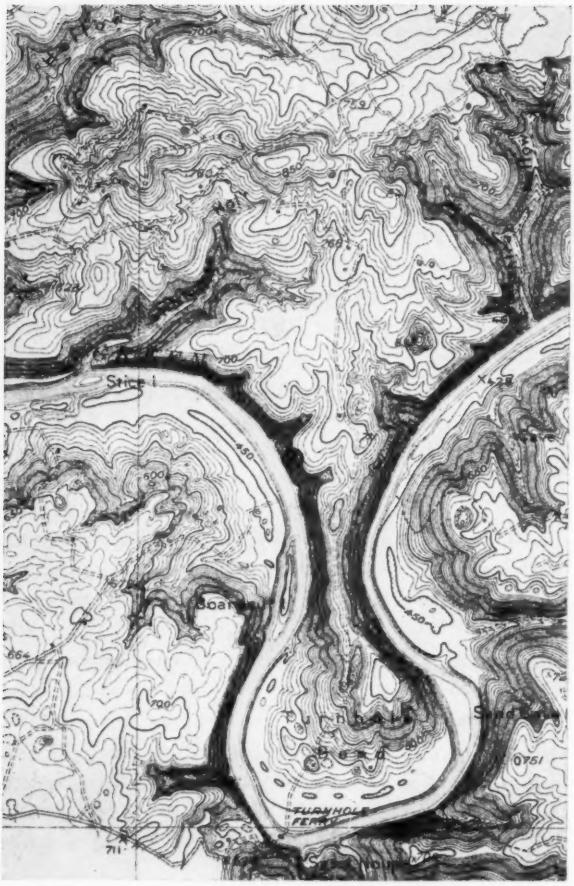


FIG. 43.—Map of Turnhole Bend and environs, near Mammoth Cave, Ky. Part of topographic map of Proposed Mammoth Cave National Park, United States Geological Survey.

floor, and for most of the cave's length there is no evidence of the presence of water.

No much greater quantity of vadose water can be asked for in earlier stages of development. Less than a square mile of upland slopes down toward the area containing the cave, a definite divide fencing off other upland areas and deep margining ravines assisting in this delimitation. Even since Green River started canyon-cutting, this tract has been thus isolated.

Furthermore, since most of the cave floor is hardly above Green River flood-levels (near the mouth, it is below), vadose water could not have started making this cave until very late in the present cycle. At such time, the surface would have attained approximately its present character, runoff going rapidly down the ravines on either side of the ridge. There simply isn't gathering-ground for enough subterranean water at present.

Nor is the cave character what is required for a vadose origin. Though not a large cavern, it has capacity comparable to many whose walls and ceilings record a subwater-table stream. Bat Cave's walls have crumbled badly, and the only solutional forms, in addition to the domepits, are a few remnants of vadose meanders, the meandering having occurred on a vanished fill close to the ceiling. The cave's capacity is about the same throughout its length, and the water it carried was a trunk stream on a low gradient.

It seems clear to the writer that Bat Cave was formed before Green River began cutting the last 50 feet of its canyon depth. On the wrong side of the river to receive downdip vadose drainage from the Mammoth Cave plateau, and severely limited in tributary slopes, it stands as a denial of Gardner's hypothesis.

THE EPOCH OF CLAY FILLING

Davis conceived of two epochs in a cavern's history: the first occurring beneath the water table and being entirely solutional, the second described as one of replenishment, the epoch of dripstone and flowstone deposition after air enters the cave. He found little evidence, convincing to him, that solutional enlargement was continued by vadose water during the second epoch. He commented a few

times on cave deposits of insoluble clay but did not see in their occurrence the record of an epoch.

Cave deposits of insoluble waste are consequences of different conditions and cannot all be genetically classified together. The class of cave deposits discussed under this heading, however, have so commonly filled the caverns to the ceiling and are so universally of unctuous clay, without sand, gravel, or flowstone, that they will be described here as "clay fills." They clearly record an epoch between Davis' first and second—an epoch which no student of caverns appears previously to have recognized.

Much information has already been presented about these fills. The stream in Smittle Cave seems about midway in the task of removing the clay by downcutting. The Missouri-Onondaga stream, attacking from below, has cleaned the clay out of most of Onondaga and made two great slump pits farther upstream, one of them in Missouri Cavern. Above the point of stream entrance, Missouri is still nearly full of clay. The stream in Meramec Cave has left terraces on the sides of its valley in the fill, the tops reaching almost to the ceiling. Farther downstream, the terraces are so wide and so close under the ceiling that a narrow trench in the clay is the only open space. By good inference, Meramec is still completely clay-filled beyond the place of escape of the stream. Mark Twain and Cameron caves are losing their clay fill down slump pits to unknown streams beneath. Craigshead Cavern, Tennessee, has some chambers with dip-determined ceilings in which the clay fill beneath, untouched by the numerous slump pits, is sloped accordingly. There is a clearance of only a very few feet. This can record only compaction of a fill once tight against the ceiling slope. Crystal Lake Cave, which seems never to have had a vadose stream, owes the headroom of its passages off the visitor's route entirely to compaction.[43] Most of Cathedral Cave retains its clay fill, headroom in much of the main chamber being largely due to compaction. Two or three slump pits add to the open space, and one huge one has been made where the stream enters the large chamber 90 feet below the ceiling, crosses, and almost immediately leaves by a stoopway-crawlway to the Mer-

[43] See J H. Bretz, "Caves in the Galena Formation," *Jour. Geol.*, Vol. XLVI (1938), p. 832.

amec River Valley. The depths of remaining clay fill shown in slump pits of several of these caves are as much as 70 feet.

Many other caves, not now possessing conspicuous clay fills, have remnants perched on high shelves. Others have conical and crescentic niches high in their walls, due, as in Endless, Mounds, and others, to the meandering of the stream which has removed a former fill and even itself may have disappeared.

The point has already been stressed that capacious caverns antedated the clay fills and that partial or complete removal has been the task of vadose streams. What conditions determined the intermediate clay-fill epoch?

The clays commonly are red, like the residual soils above. They lack all evidence of current, they show little evidence of any kind of fluctuations during deposition. Even good lamination is not common. Complete lack of flowstone, dripstone, and rimstone indicates the absence of air while the deposit accumulated. The fills appear to be subterranean lake clays, made beneath the water table.

Yet many chambers now or formerly containing them obviously were trunk routes for ground-water discharge. The marked stagnancy required for deposition of the clay in such chambers succeeded a fairly definite flow, though both epochs were phreatic.

Here the evidence, so far as collected, ends. Beyond this lies speculation and opinion, limited by the following considerations. (1) It is impossible to derive complete clay fills from the insoluble material of the limestone which has disappeared. (2) It is impossible to explain the older cavern forms as gradually being filled at the bottom while being dissolved at the top. (3) It is impossible to use glacial waters or Pleistocene pondings to explain fills far from the influence of the continental glaciation.

A satisfactory explanation for clay fills must also take account of several phreatic caverns, notably Carlsbad, which appear never to have had the experience.

In accord with known cavern patterns, we may picture many subwater-table streams as anastomosing flows through a plexus of enlarged routes, not necessarily all concentrated in one underground route and not necessarily all in one plane. There may even be crossings of one member by another, relatively thin floor-roof separations

existing. Examples of this relationship in Mammoth are the thin floor of Broadway over Blacksnake Avenue, and the obviously once-separated condition of Gothic Avenue and Broadway and also of Cleveland Avenue and an unnamed big conduit crossing above it, whose floor collapse has in part produced the "Rocky Mountains" pile of fallen fragments.

With such relations among the big ducts close under the water table, changes in course as passages are enlarged can readily be visualized. This could leave some chambers isolated, in condition to fill with clay. So also could blockades of fallen rock, like those at either end of Round Spring Cavern, if the cave were still below the water table. Surface valley deepening might tap main underground routes, determine new exits, and thus leave some chambers deprived of their former flow. Among these possibilities, there seems ample opportunity for replacing flowing with standing water, beneath the water table.

It is unnecessary to have subwater-table streams in the picture. Clay fills like that of Crystal Lake are in caves that never have had streams of any kind. Mark Twain and Cameron are examples of caves which had no flowing water in the system until after the clay fill was completed.

Derivation of the clay is no problem once joints down from the surface have become enlarged. Doline development will yield still more clay, and this very fine-textured material, becoming widely spread in the underground system, will come to rest in chambers offside from still-functioning routes.

Additional support for this view of clay filling before the lowering water table has passed the cave level is found in other types of cave-floor deposits. Much clay may be found in them, but also silt, sand, and gravel. Commonly, bar forms exist on the inside of curves, with accretions recorded by stratification paralleling the curved vertical profile of the bar and exposed by trenching across the bar. Trinkle Cave, Indiana, has such bars along more than half a mile of length and still has the stream which made them. Round Spring Cavern shows abandoned bar forms, with interbedded flowstone sheets in some of them. Stronger cave streams may carry sand and gravel, as in numerous passages in Mammoth, associated with flutes and

potholes which record the same flow as does the current-bedded sand. These deposits are part of the vadose record, later than and notably different from the clay fills of phreatic origin.

This intermediate epoch of clay filling may be omitted from a cavern's history without invalidating the concept above outlined. Indeed, all solutional stages between the initial phreatic anastomosis and a final meandering free-surface flow may also be omitted. In Wilson Cave is a beautiful showing of a bedding-plane anastomosis from which a meander slot has been cut down into limestone beneath. No large phreatic chamber ever was formed, and no clay fill. One measured meander arc here is 30 feet wide, 2 feet in average height, and 6 feet in total vertical range. The only deposit is gravel and it generally is thin. Also, passages in the southeastern end of the phreatic complex along Ganter Avenue, Mammoth Cave, show remarkable curving, sloping slots cut *de novo* in limestone.

Somewhat more of a problem, however, is Carlsbad, which grew to be a huge phreatic spongework and there rests today; only dripstone, flowstone, rock falls, and local detrital fills interrupting the pattern and altering the primitive forms. If Carlsbad's problem is to be discussed at all, it must be preceded by sufficient detail regarding the cavern's physiographic setting.

HISTORY OF CARLSBAD AND SLAUGHTER CANYON CAVERNS, NEW MEXICO

Both of these great caves occur in the eastern margin of the Guadalupe uplift, only a few thousand feet back from the edge of the escarpment of Permian limestone which overlooks the Pecos Valley (Delaware Basin) to the east. Carlsbad's entrance is in the summit of the scarp, 1,000 feet from the brink and about 550 feet above the near edge of the lowland. Slaughter Canyon's entrance is almost as high and almost as near the scarp face but, as the name implies, is in a canyon wall. Carlsbad's depth is about twice the height of the escarpment.

Traced across the Carlsbad Cavern National Park topographic map, both the base and the brink of the scarp rise 400 feet in a distance of 6 miles and the front departs not more than 600 feet from a straight line in that distance. This scarp extends across unmapped

areas for many miles to the southwest, gradually becoming higher until in Pine Top Mountain, near El Capitan and Guadalupe Peak, Texas, its summit is 2,000 feet above a base that has risen an equal amount in that distance of 50 miles. This is the eastern side of a great triangular block, the Guadalupe uplift, the south-pointing prow and highest point of which is Guadalupe Peak. On the western side of this block is an even higher scarp.

The streams on the back slope of the uplift in general flow with the dip, have linear courses determined by intra-block fault scarps and by joints, are gathered into a few large streams which trench the

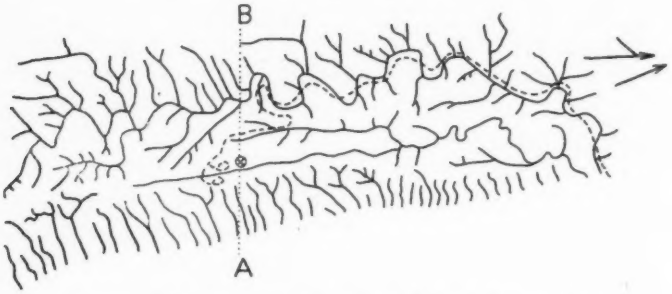


FIG. 44.—Drainage pattern in vicinity of Carlsbad Cavern, N.M.

scarp faces in escaping to adjoining lowlands. In the vicinity of the two caves, there are miles of scarp front without a canyon notch. Multitudes of short, gully-like ravines furrow the front, averaging less than half a mile long, none as much as a mile, and so shallowly entrenched that their gradient (about one in seven) is more than half as steep as that of the undissected portions of the scarp.

Figure 44 shows the extraordinary relation of streamways on top of this part of the uplift to the scarp and its short ravines. Figure 45 is a cross section at the Carlsbad entrance showing the exposure of Bat Cave Canyon's course to piratical action by dozens of the steep-grade ravines but without that action having yet occurred in a single instance. All this argues for youthfulness of the scarp, for a diastrophic origin.

Another interpretation of the scarp is that it is the eastern slope

of the great Capitan reef and that the Pecos lowland to the east has been erosionally produced in softer and more soluble fore-reef beds, anhydrite and halite as well as clastics and limestones.

Walnut Canyon, entering the lowland $3\frac{1}{2}$ miles from Carlsbad Cavern, has an average gradient of 66 feet per mile in the lower 9 miles of length and has incised inherited meanders to make the beginnings of a flood plain on the inside of its curves. The summit of the linear divide between Walnut and Bat Cave canyons has a gradient of about 100 feet to the mile in the same direction; perhaps structurally determined, possibly the record of a tilted erosional

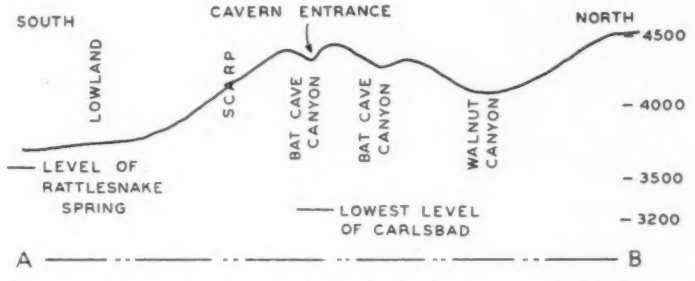


FIG. 45.—Cross section of scarp and upland valleys at entrance to Carlsbad Cavern. Vertical 3× horizontal.

plane. Walnut's lower gradient is largely because of the growth of meanders. The canyon has the same depth 9 miles upstream as where it crosses the scarp.

From the 300-foot depth of this canyon, it may be argued that a lowland to receive the canyon's drainage has existed or has been contemporaneously developing for a long time and that, during this time, the reef front has been exhumed to make the little-dissected scarp. In such case, youthfulness of the scarp would be consequent on (1) superior resistance of reef rock and on (2) earlier existence (and persistence) of the divide between Bat Cave Canyon and the brink of the scarp.

Farther southwestward and across the state line, the presence of the fore-reef and sub-reef Delaware Mountain group in the scarp base seems to require faulting and flexing to produce the great

cliff.[44] Here, also, the scarp is erosionally youthful, and drainage on the top of the block is extraordinarily dilatory in finding escape, either eastward or westward, to closely adjacent country hundreds, even thousands, of feet lower. The writer believes that, even in the region of the caves, geologically recent movement probably should be part of any acceptable explanation for the scarp.

The cavern entrance at Carlsbad is 4,350 feet A.T. The floor of the Big Room is 3,600 feet A.T., and deeper levels certainly reach as low as 3,300. There is little drip water and no stream water at any level and, through the cave above 3,600,[45] no trace of any for-

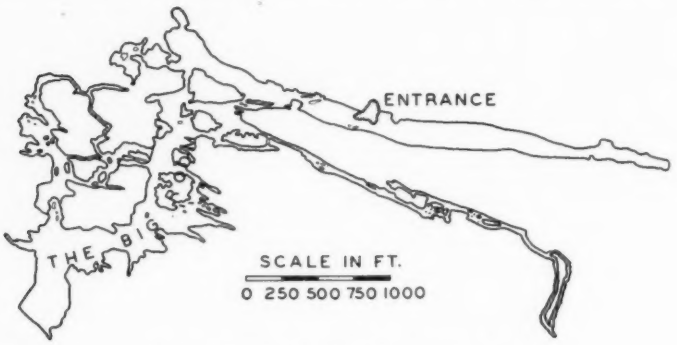


FIG. 46.—Map of Carlsbad Cavern (after Lee)

mer stream. Yet the good-sized Rattlesnake Spring (7 second-feet) emerges in the gravel-covered lowland near the base of the scarp, 5 miles from the cavern mouth, at 3,634 feet A.T. It is not draining any cave as deep as Carlsbad and its course before emergence does not utilize any known cave in the Guadalupe block.

Carlsbad's descent to the Big Room is a long irregular diagonal dipping westward, away from the escarpment.[46] The cave's ground

[44] N. H. Darton and associates, in several publications, have commented on, diagrammed, and mapped fault and flexure deformation in the eastern scarp of the Guadalupe block, though Darton's latest remarks and diagram (*Guidebook 13, 16th Internat. Geol. Cong.*, [1933]) indicate that at the cave the scarp is an erosional truncation of the strata, a cuesta front. The writer is sure it is not the front of a retreating cuesta.

[45] The lowest levels were not open to inspection.

[46] Both Darton and Lee have diagrammed it as dipping toward the scarp.

plan shows definite control by east-west and north-south joints. Though there has been enormous enlargement at intersections, it is still a joint-determined network without later experience with even subwater-table streams.

Lee's concept of the trapping of insoluble waste from the surface while en route through a cavern[47] is exemplified in a few half-full chambers but is far better shown in other caves than Carlsbad. In these limited deposits there are no definite records of streams through the cave system. The absence of terraces of sand and clay, of remnants of fills on high shelves, and of graded fill floors is in harmony with the absence of all solutional forms ascribable to free-surface streams.

Carlsbad and Slaughter Canyon caves predate the scarp, however that was formed. Integration of subterranean drainage to make gradient-directed underground streams, manifest by several springs in this part of the Guadalupe block, has come about during and since the making of the scarp. But this drainage has not used any known big-cavern routes. The empty chambers 300 feet lower than spring mouths testify that the discharge today must be by perched, or superwater-table, streams.

Carlsbad and Slaughter Canyon caverns, made before ever a scarp existed, made probably while younger formations still overlay the Carlsbad-Capitan limestone, have simply been drained of their phreatic water and replenished with dripstone of fittingly heroic proportions. Neither of the experiences the writer has stressed in this paper—the subwater-table stream flow and the clay fill—have been theirs. They are ideal exemplifications of Davis' two-epoch theory.

Mammoth's dominant chamber type of uniformly cross-sectioned, evenly floored, riverward-elongated galleries nowhere occur in Carlsbad. Mammoth's ridge-top ponors and dolines are almost totally lacking in the Carlsbad region. There are no uvalas separating the ridges. Sink development has never been a part, even as a consequence, of cavern development. It is difficult to understand how Gardner's picture could ever have been hopefully applied to Carlsbad.

[47] W. T. Lee, "Erosion by Solution and Fill," *U.S. Geol. Surv. Bull. 760* (1925), pp. 107–21.

CAVERN-MAKING IN THE EROSION CYCLE

Thus far in this paper, Davis' concept of cave sequences has been presented as two-epoch; solutional excavation followed by dripstone-flowstone replenishment. The event separating the two epochs is the sinking of the water table past the cavernous horizon, this sinking consequent on deepening of surface valleys.

Davis has not been unchallenged on this two-epoch concept. Swinnerton's belief that caves develop chiefly at the water-table level allows him to see dripstone deposited "whenever the cavern is largely air filled," inferentially long before full cave growth has been attained.

In the present study, much evidence has been submitted to support the idea of cave growth in the completely saturated zone, therefore the actuality of Davis' two epochs. Also an intermediate epoch of clay filling has been argued for, a definite marker in many caves between the two epochs of Davis.

But the master-physiographer saw farther than the sequences of existing caves. He looked into the future of the present erosion cycle, saw peneplanation approaching, visualized under that peneplain-to-be the ground-water circulation his advocated principles required, believed in "cavernous galleries .... hidden below a limestone peneplain." He looked into the past, saw an earlier erosion cycle far along toward peneplanation in the cavernous regions of the Mississippi Valley and the Appalachians. The caverns, therefore, he believed, dated from the older cycle, were chiefly being drained, exposed and dripstone-filled in the present cycle. The two contrasted epochs of cave history had been made possible by the two cycles of their regions' history.

Davis realized, however, that, in attainment of one cycle's maturity, enough water-table lowering may have occurred to drain phreatic caverns developed during its youth, and to yield the two-epoch history. Thus "an imitation of a two-cycle cavern may be made from a one-cycle cavern. But of the two causes of transference [above the water table] regional elevation is much the greater."

Are the caverns in the hills and ridges phreatic in origin? Pages of answers for this question have already been given. The writer believes that most caverns he has seen are largely phreatic.

Are these phreatic caverns "imitation" two-cycle features? In reply, one might propound the counterquestion: "If caverns *are* largely phreatic and peneplains are therefore likely to have caves hidden beneath them, what can these caverns be except relics of that peneplain?" Much better, however, would be definite evidence, pro or con.

Clear-cut and positive evidence on the problem has been impossible to secure, thus far. There are other possibilities of interpreting the data, and these alternatives will be variously weighted by different readers.

THE BLUE MOUNDS REGION, WISCONSIN

Projecting westward two-thirds of the way across the Driftless Area of Wisconsin is Military Ridge, a north-facing cuesta capped by the Galena formation. Both the face and the back slope of the cuesta are maturely dissected, but the top is fairly broad and in its summit areas are remnants, according to A. C. Trowbridge,[48] of two peneplains, the Dodgeville at about 1,400, the Lancaster at about 1,250. F. T. Thwaites[49] believes in only one peneplain, the Lancaster, holding that the Dodgeville remnants are only residual hills of that surface. R. E. Bates[50] argues for one peneplain also, but his is the higher Dodgeville. By him, the more extensive Lancaster remnants are records of an incomplete erosion cycle, later than Dodgeville but preceding the present. Lawrence Martin[51] long ago discarded the peneplain hypothesis entirely, holding that structure has determined the broad summits.

Near the eastern end of the Military Ridge summit stand two prominent flat-topped hills, the Blue Mounds. The western Mound, 1,716 feet A.T., is held up by a cap of completely or almost completely silicified Niagaran strata. The eastern and lower Mound,

[48] "The Erosional History of the Driftless Area," *Univ. of Iowa Studies No. 40* (1921).

[49] "Physiography of the Baraboo Area," *9th Ann. Field Conference, Kans. Geol. Soc.* (1935), pp. 395–404.

[50] "Geomorphic History of the Kickapoo Region," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 819–80.

[51] "The Physical Geography of Wisconsin," *Wis. Geol. and Nat. Hist. Surv.*, Bull. XXXVI (1st ed., 1916; 2d ed., 1932).

1,488 feet A.T., has lost this cap, but all its slopes carry boulders of the chert. The higher Mound is a monadnock to all but Martin, the lower one and the saddle between the two may be considered a remnant of the Dodgeville peneplain by some, or simply a residual elevation on the Lancaster peneplain by others.

Today's drainage pattern on the cuesta almost certainly reflects that of the region before dissection. The predecessor of Military Ridge was a low stream divide on the oldland, or oldlands, with a prominent monadnock standing on its crest. It was therefore also

FIG. 47.—Blue Mounds, Wis. Part of Blue Mounds quadrangle, United States Geological Survey.

a ground-water divide, as it is today. This point must be accepted, whomever the reader follows on the physiographic history. It is an important point, for three caves occur in the immediate vicinity of the Blue Mounds, one of them no longer enterable, two of them already described in this paper as phreatic in origin.

Cave of the Mounds is approximately 1,350 feet A.T. and less than half a mile south of the 1,480 summit flat of the eastern Mound. It is entered from a quarry in the side of a ravine 30–40 feet deep here in the slope. The ravine never intersected the cave; the two are connected only because of the quarrying. One elongated portion of the cave leads northeastward under a flat-topped shoulder of the Mound about 1,400 feet A.T., but the main chamber, now blockaded,

appears from a well log to lead northward under the hilltop. That this chamber extends much beyond the fallen rock blockade seems obvious from its original uniform, conduit-like cross section.

The maximum area that today could contribute to Cave of the Mounds subterranean drainage is but little more than a quarter of a square mile. This would probably suffice for the small meandering vadose stream so remarkably recorded in the cave's complex of wall-incised meander niches (p. 682). But never, while the near-by, lower, and well-dissected back slope of the cuesta has existed, could this drainage area have kept the main chamber full to make the joint-determined ceiling cavities. The cave is older than the present dissection.

The cuesta is retreating southward, downdip. Some of the south-draining area has surely been lost to the north slope's steeper ravines during the present cycle. But the two Mounds, standing about a mile north of the general east-west trend of the present divide, seem to record less of a retreat than that suffered by the rest of the divide. Since, furthermore, the northern slopes of the Mounds are no steeper than their southern, it seems unlikely that the quarter-section above referred to can possibly be more than doubled or trebled for earlier subterranean vadose drainage.

Another feature of the eastern Mound that may belong in the picture is a long, narrow, vertically walled sink on the northern slope at about the level of the cave. It is elongated along the regional dip and surely is due to collapse of a cave chamber comparable to the main chamber of Cave of the Mounds. It may be, therefore, that this cave's system runs completely through the Mound. If this be so, the cave is older than the isolation of the Mound—a conclusion just reached from the size and phreatic origin of the part of the cave now enterable.

Thus we may visualize an oldland, only a fragment of it now remaining in the Mound's flat top. No deep Wisconsin Valley, ten miles distant, then paralleled Military Ridge. Only a gentle slope descended northward to the Dodgeville Wisconsin. To allow for subsequent cuesta retreat, the water-parting may be placed somewhat farther north than the present Military Ridge crest; so therefore should be the ground-water divide. Drainage down the cuesta's

gentle southern back slope today goes several times as far to a master-valley. Presumably this oldland also had a gentler southern than northern slope. Under these conditions downdip ground-water flow through the cave was leisurely, and the nearness of the ground-water divide to the cave is not a denial of the validity of the picture. Cave of the Mounds comes close to Davis' concept of a cave developed beneath a peneplain.

Pokerville Cave, south of the larger Mound, has an altitude of about 1,280. It lies just below the broad top of a ridge between two valley heads of the Mound's southern drainage. Like Cave of the Mounds, Pokerville Cave has never been intersected by surface valleys, is entered through an artificial cut. The altitude of this ridge top is approximately that of the Lancaster surface. Like Cave of the Mounds, Pokerville is in large part phreatic. There is a complex three-dimensional network below the tube described with the meander slots in the bottom (p. 692), and it is down into a portion of this network that the vadose water of today is drained. Pokerville chambers are smaller than those of Cave of the Mounds, lie at a lower altitude, and are farther from a higher summit. The drainage area for ground water is no greater than for the other cave, nor could it have been greater earlier in the present cycle. Neither cave's phreatic history could have included experience with a subwater-table stream with velocities like those in Missouri. Pokerville, like Cave of the Mounds, must date back to a time of low gradient for both surface and subsurface water, to an oldland where now stands Military Ridge. Though the monadnock summit, a mile to the north, is more than 400 feet above the cave ridge top, the ground-water gradient at the cave must be judged by the near-horizontality of the tube.[52]

It is difficult to be more precise in interpreting this physiographic history. We cannot be sure that either cave grew at its present depth below the existing upland surfaces, and we cannot decide among the rival histories for these surfaces. But we do know that Cave of the Mounds is 100 feet or more higher than the average crest of Military Ridge, yet records an integration of rather slow-moving phreatic

[52] Since present dissection has developed, the gradient has been steepened, but only vadose water has been present to take advantage of it.

flow. A land surface for the region, somewhat above cave level, is essential for this. Either that surface was an oldland, a peneplain across the Galena formation here, or the cave must have been formed still earlier in removal of the Paleozoics from the region. If the Cave of the Mounds system should ever be shown to underlie the eastern Mound itself, this second alternative would have more support.

Similar in some ways to these Blue Mounds caves is Eagle Cave, a few miles north of Wisconsin River and some 30 miles farther west than the Mounds. It is a hilltop cave, close to the surface of the ground, 200 feet above the bottom of adjacent, steep-walled ravines and 300 feet above Wisconsin River. Yet along its length it is essentially horizontal. Solution forms on walls and ceilings have been destroyed by rock falls. The cave pattern suggests, but does not establish, a subwater-table conduit. Low gradient of the flow is clearly recorded, hence the conviction that the present hilltop was but part of a lowland when the cave was a functional drainage way. The hilltop is all of 100 feet below a fair estimate for the Lancaster Wisconsin's valley floor. Eagle Cave might be post-Lancaster but quite surely is a relic of an erosional lowland and must antedate the present cycle.

THE MAMMOTH CAVE REGION

Across the edges of the warped Paleozoics of central and western Kentucky, various peneplain remnants and traces have been recognized by different authorities, the correlations of which with each other and with Appalachian erosional surfaces are still unsettled. The crest of the Dripping Springs escarpment (p. 761) and higher parts of the backslope of the cuesta (the Mammoth Cave plateau) west of it are accepted as traces of such a peneplain.

All must agree that the escarpment has been retreating westward, downdip, and that the lower Pennyroyal surface occupies territory abandoned during this retreat. Since this surface truncates both St. Louis and Warsaw rocks, it is not determined by structure. The St. Louis is accounted as no more resistant than the Ste Genevieve, and, if so, there is only one reason why the St. Louis is not in the escarpment face instead of being in the Pennyroyal floor. It is that

the Pennyroyal surface was developed at baselevel, a later and lower baselevel than that recorded in the Mammoth Cave plateau top.

Is the Pennyroyal surface due largely to escarpment retreat during this later cycle? One must take account of the following items when in search of an answer.

1. The Cypress sandstone, capping the higher plateau, has protected that upland so well against stream erosion through the Pennyroyal cycle and subsequent time that the plateau is fairly intact today.

2. Where the sandstone has been removed in dissection of the plateau, more successful attack has been made by solution of the underlying limestone (uvalas) than by Green River and its tributaries trenching from above.

3. The sandstone-protected escarpment today is a definite feature, shows no evidence of softening down or of increasing raggedness of front. It is, as Dicken says,[53] a solutional escarpment, not the result of stream and slope erosion.

4. On the lower Pennyroyal plateau, sandstone-capped residual hills are rare. Pennyroyal has lost almost every vestige of the Cypress sandstone. Yet there are no through streams over many square miles of the surface, by which the waste could have been carried away.

5. Pennyroyal surface drainage flows toward and crosses the escarpment to enter the Mammoth Cave plateau area. It did this during the Pennyroyal cycle, also.

6. The large streamless areas of this lower surface are drained by subterranean routes, also flowing toward and across (beneath) the Mammoth Cave plateau. The stream pattern does not suggest that Nolin, Green, or Barren rivers (where on Pennyroyal) have lost territory to this subterranean drainage. Hence ground-water routes were probably as important during the production of the Pennyroyal surface as they are today.

It appears, therefore, that escarpment retreat, largely because of solutional attack on the Ste Genevieve limestone, has made the Pennyroyal surface in large part.

If one visualizes the former eastward extension of the Mammoth

[53] *Op. cit.*

Cave plateau, he must also visualize a drainage for it comparable to what the existing portion now has; a multitude of little streams working on the sandstone top, a few main valleys down through the sandstone into the limestone, and (somewhat later) numerous deep depressions with subterranean drainage beneath the sandstone-capped upland. For making those sinks, he must use the mechanism and sequence already outlined (p. 765); caverns first, then ponors, then dolines, finally uvalas. The caverns drained in general down-dip. They were continuous from the vanished portion (now the Pennyroyal region) to and through the surviving portion (Mammoth Cave plateau). Their remnants in that plateau are the higher chambers of Mammoth, Colossal, Collins Crystal, Great Onyx, Salts, etc. Mammoth Onyx, in an outlier of the plateau, is a segmented and isolated part of the vanished cave system. If the criteria described in this paper are valid, these were phreatic caverns, subwater-table streams in so far as they were main routes, networks and spongeworks, and bedding-plane anastomoses where there was no demand for main routes.[54]

This interpretation of genetic relations between caverns and surface history of the Mammoth Cave region does not date the caves as definitely earlier than the Pennyroyal cycle. Perhaps they are "imitation" two-cycle caves after all. Perhaps they grew while that part of Mammoth Cave plateau to the east was being destroyed by scarp retreat. There are three items to be examined, however, before a conclusion is justified.

One is the depth of the higher chambers of these caves beneath the plateau top. Phreatic main conduits of one-cycle origin could hardly be expected close to the upland surface, whereas some such conduits beneath a peneplain might well be developed at slight depth. Mammoth and Colossal caves contribute no positive evidence, for none of their known main chambers are close to the broad

[54] The writer dislikes the practice of identifying five or more "levels" in Mammoth, believing that these have no genetic meaning if, indeed, they have an objective existence. He does not believe in a definite and rigorous sequence of development whereby a higher passage must be abandoned as an immediately lower one grows. Since all grow below the water table, several "levels" may be simultaneously functional, and abandonment will come only as the deepening main river valleys lower the water table enough to drain the higher cavities.

ridge tops. Floyd Collins Crystal and Salts caves, however, have capacious, linear, nearly horizontal chambers, hardly if any more than 100 and 150 feet below the peneplain remnants of the upland and close to the top of the Ste Genevieve formation. At Salts Cave, more than 100 feet of the ridge summit is Cypress and younger rocks. Though these chambers seem high in the hills for one-cycle caves, the figures alone may not convince everyone that they are two cycle affairs.

Another item deals with a curious restriction of the uvalas to one part of the Mammoth Cave plateau and a coinciding restriction of dense populations of the shallow Pennyroyal sinks (without surface streams) to an area updip from the uvalas. This relationship is well shown on the Mammoth Cave and Horse Cave topographic maps of the United States Geological Survey. West of the longitude of Turnhole Bend on the Mammoth Cave map, there are no uvalas in the upland and few sinks in the lowland close to the foot of the escarpment.

Echo and Roaring river water undoubtedly is supplied by these lowland sinks, the subterranean drainage entering the St. Louis limestone and reappearing near Green River in the basal part of the Ste Genevieve.

Since the uvalas need pre-existing caverns for their initiation, it seems a plausible idea that subterranean drainage from the southeast has been passing during all Pennyroyal time under that part of the Mammoth Cave plateau now marked by caverns and uvalas. Where uvalas have not developed, caverns did not (and do not) exist, nor did (or does) a dense population of Pennyroyal sinks exist. The Scottsville and Bowling Green topographic maps show the Pennyroyal sinks to be much more numerous near Barren River than near the uvalaless plateau. Barren River here on the lowland seems to be taking care of ground-water discharge, seems to have done so during the Pennyroyal cycle.

The writer believes that this association of abundant lowland sinks and numerous upland uvalas must have a causal explanation. Because Echo and Roaring water bodies in the cave are clearly supplied by subwater-table streams, and most Mammoth Cave chambers record such streams of the past, the writer pictures com-

pletely water-filled conduits functioning today beneath the uvala-and-cavern marked region.

Yet when the Pennyroyal cycle was in its youth, the escarpment stood farther east than now, and these streams were at least twice as long as today. They were flowing beneath the newly uplifted Mammoth Cave peneplain. They did not bore their way northwestward beneath that plateau. Favorable conditions for the localization of this subterranean drainage must have already existed. The upland uvala and lowland sink association seems therefore to hark back to cavernous routes already developed beneath the Mammoth Cave peneplain. If this is correct, the caverns of the Mammoth Cave region are two-cycle features.

The third item to be considered in this problem is that of caves beneath the Pennyroyal lowland. There apparently are but few known, which to the writer means few that have been drained of ground water. One of these is Lost River Cave, about 2 miles south of Bowling Green. It lies about 5 miles out from the rather ragged escarpment front, its immediate environs being a gently rolling plain with a relief of about 50 feet. Five or 6 miles farther out from the scarp, Drake's Creek and Barren River have meandering valleys sharply incised about 100 feet deep in this part of the Pennyroyal plain and almost wholly lacking in surface tributaries. In the vicinity of the cave, sinks are not numerous or deep. An equal area between Drake's Creek and Barren River, 5–10 miles from the cave, has several times as many sinks, averaging two or three times as deep. The Pennyroyal peneplain south of Bowling Green is about as well preserved as the Somerville at Baker Caverns, Pennsylvania.

The cave is entered from the northwest end of a steep-walled sink 75–100 feet wide and 1,500 feet long. Half of the sink's periphery is cliffed and most of its bottom is irregular with heaps of fallen rock fragments. Several deep ponds lie among these heaps. Lost River itself emerges from a deep pool near the northwest end of the elongated sink, flows a short distance toward this end, and there enters the cave, back in which it disappears as the roof descends to the water-level. The broad flaring cave mouth in the end wall of the sink is due to enlargement by weathering. Only the orchestra alcove in the cave's dance hall now records phreatic solutional attack on

FIG. 48.—Vicinity of Lost River Cave, near Bowling Green, Ky. Part of Bowling Green quadrangle, United States Geological Survey.

the walls. The stream is 60–70 feet below the plain and has a good gradient in the exposed part.

Another sink, similar in size and shape to, and in line with, the one examined, lies a short distance to the southeast. Still farther southeast, a small creek flows northwest along this same line, disappearing underground about 2 miles from the nearer sink. Very probably this creek contributes to Lost River.

Lost River flows (diagonally) away from the near-by Drake's Creek Valley. Though it flows toward Jennings Creek Valley 1½ miles distant along the northwest-southeast line of the sinks, it is at least 20 feet lower than the creek where intersected by that line. The further course of Lost River is unknown, but it certainly is not tributary to any near-by surface stream and therefore has not developed because of their existence. The sink surely postdates the solutional cave. For these reasons, the subterranean stream course, partially exposed by fairly recent collapse, is considered as older than the surface valleys. It is still a subwater-table stream except where the roof has fallen in. It is an inheritance from the Pennyroyal's subsurface drainage.

SHENANDOAH VALLEY CAVERNS

The broad lowland known as the "Great Valley of the Appalachian folded belt" is drained by several rivers, all of them escaping through watergaps across margining mountainous ridges. That part of the Great Valley in northern Virginia, drained by the Shenandoah River, is divided into two valleys for a distance of 45 miles by the complex synclinal Massanutten Mountain group, each valley carrying a northeast-flowing fork of the Shenandoah. The mountain group stands completely isolated on the valley floor. One can reach it without crossing a stream only from the west and near the south end of the mountain. Here, in the vicinity of Harrisonburg, the wide valley floor, truncating folded and faulted Paleozoic formations, has an altitude of about 1,400 feet A.T., with some hills (notably Chestnut Ridge) reaching 1,500 and 1,600 feet. Here the valley-floor drainage is divided, some going southward to the South Fork and some northward to the North Fork. This is the least-altered part,

in northern Virginia, of Stose's "valley-floor peneplain,"[55] though that peneplain is readily recognized from broad accordant lowland hilltops as completely surrounding Massanutten Mountain.

About 6 miles southeast of Harrisonburg, close to the western foot of the mountain, is Massanutten Caverns, its level but little above

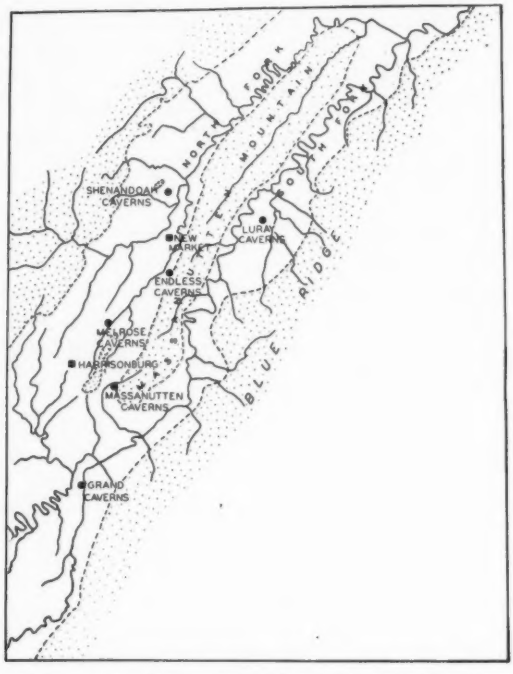


FIG. 49.—Sketch map of part of Shenandoah Valley, Va.

the broad bottom of near-by Cub Run Valley. Elongation of the cavern system is with the strike of the two Stones River formations involved in the cave. That part of the cavern opened for visitors is a network in a horizontal plane. The ceiling, where not concealed by dripstone, is a solution feature smoothly truncating the bedding or diversified with pendants and joint-determined cavities. The pres-

[55] G. W. Stose, "Physiography," *Va. Geol. Surv. Bull. 23* (1922).

ent floor is a clay fill, but two lower levels are noted by W. M. McGill[56] and reported by the management to lie 30–40 feet deeper and to have ceilings similar to those of the main level. The picture thus is of a three-dimensional cave system in strata dipping about 60°, the upper level certainly a definite network along joints and strata, its horizontal dimensions far exceeding the vertical and largely subparallel with the strike.

Water-table control seems an inescapable conclusion. Perhaps two or three successive water tables are recorded. No gravity stream

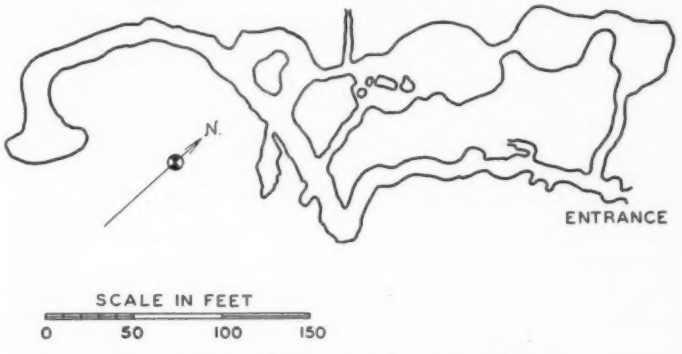


FIG. 50.—Map of Massanutten Caverns (after McGill)

made this pattern of the upper level, nor the joint-determined cavities in walls and ceilings. No such stream now flows in the lower levels close to the present water table. The entire cave, as far as now drained, was formed beneath the water table of the valley-floor peneplain. Later free-surface stream work has done little more than to remove part of the fill.

Endless Caverns, like Massanutten Caverns, is close to the western foot of Massanutten Mountain and is in the Stones River group. The dip is less, however, ranging from 16° to 25°, and the altitude of the cave mouth is only about 1,200 feet. This is the altitude of most near-by summits, remnants of the valley-floor peneplain, in the North Fork lowland in this latitude. Endless, however, lies under a

[56] "Caverns of Virginia," *Va. Geol. Surv. Bull. 35*, 1935.

slope which is post-peneplain in origin. Smith's Creek, a mile from the cave, has a broad valley bottom, 200 feet lower, developed since uplift of the valley-floor peneplain.

The history of Endless has already been outlined (p. 740). Most of the cave's capacity existed before an epoch of filling occurred, and all recorded vadose experience has been contemporaneous with or later than the filling. Almost complete removal of the fill has made the replenishment epoch possible.

The phreatic conditions under which Endless was made must date back to the valley-floor peneplain. The filling may have occurred late in that stage or early in the peneplain's dissection. The meandering free-surface stream and its work in removing the fill had to wait upon the deepening of Smith's Creek Valley, that is, the dissection of the peneplain.

Melrose (Virginia) Caverns lies $3\frac{1}{2}$ miles away from the foot of Massanutten Mountain, about a third of the way across the North Fork broad valley, and 5 or 6 miles from the Chestnut Ridge remnants of the valley-floor peneplain's divide. The cave is in the valley of Dry Fork, a tributary of Smith's Creek, at an altitude of about 1,250. Near-by hilltops are 150–250 feet higher. Here, again, Stones River formations constitute the cavernous rock, their dips ranging between 12° and 16°. Azimuth of chambers is controlled in part by bedding strike, in part by the strike of joints, though Melrose is not a network cave.

Fine ceiling pockets and joint-determined ceiling cavities are common in Melrose. En echelon overlapping of linear chambers occurs, with or without exposed perforations. Some passages are essentially tubes, others taper up into narrow slots along the joints. Neither cross section can well be a cave-floor stream's product. At the far end, the cave is a spongework of chambers, as diversely shaped and placed with reference to each other as in any spongework of average-sized cavities.

The fill in Melrose was introduced under vadose conditions, as is shown by the bits of chert and flowstone in the clay. The clay shows little or no stratification, and the limestone walls have no crescentic niches like Endless and no half-cone niches of the Smittle type.

Whether the chert came in through sinkholes like the two which now breach the roof or by way of a cave-floor stream is not clear.

The original cave appears to have been cut in two by surface-stream erosion, Big Mouth Cave on the opposite side of a small adjacent valley being the severed portion. The writer cannot accept McGill's tentative explanation that "the stream which excavated these caverns originally entered the limestone through small surface fissures or the sink holes near the rear of the caverns" and emerged "as a spring feeding into Dry Fork at a point on the northeast slope of Cave Hill." The hill, which is essentially perforated by the cave, is much later than the cave-making. The sinkholes and the possibility of a spring are consequent on the existence of the hill.

That Melrose has carried a subwater-table stream is not clear. Some parts are correctly proportioned to fit the concept, but the great spongework needs no current and records none. If Melrose was developed beneath the valley-floor peneplain, its depth was at least 150 feet below that surface. This is the figure supplied by the management for the height of the hilltop above the uniform cave level.

Shenandoah Caverns lies near the middle of North Fork's broad lowland, its entrance 1,030 feet A.T., less than a mile from the river 100 feet above it. The approximate altitude of peneplain remnants in the vicinity is 1,200 feet. Third Hill, 2 miles from the cave, rises to more than 1,600 and must be considered a small monadnock on the valley-floor peneplain. The cave has a vertical range unusual in this region, amounting to a little more than 200 feet. Its lowest portions are about 50 feet above river-level, its highest about 40 feet under the top of the hill.

Shenandoah is a network cave, bedding and jointing of about equal importance in determining chamber orientations. Openings along the stratification have ceilings that slope some 35° with the dip of the Conococheague limestone and generally are not high rooms. Along the nearly vertical joints, ceilings may be 50, 75, and perhaps even 100 feet above the floor.

So much rock has fallen in parts of Shenandoah that some solutional chambers have been completely filled, and new chambers entirely of collapse origin surmount them. Some fallen blocks show

subsequent solutional attack, and the great vertical extent of this cave may be due in part to this stoping of roof material which then was dissolved away on the floor.

The network pattern testifies to the phreatic origin of Shenandoah Caverns. One particular room, an epitome of the cave scheme, consists of a low passage along the strike of the bedding, its ceiling determined by the dip but intersected by three narrow, lofty, nearly vertical, parallel, joint-determined passages. The walls separating the joint openings are 10–20 feet thick but, as in Grand Caverns, are perforated by numerous windows of various sizes, shapes, and locations. Many potential windows were only wall pockets along the strike when solution ceased. Some of them are long, shallow strike slots, some are deep and narrow, none is like the horizontal groovings and undercuttings made by cave-floor streams. They are phases of differential solution where current was not a factor.

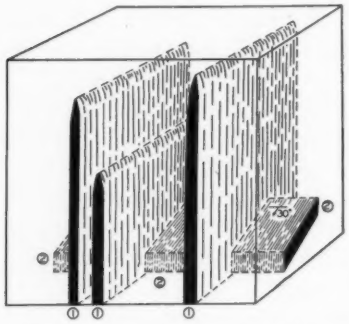


FIG. 51.—Diagrammatic depiction of the relations of cavities along (1) the vertical dip joints and (2) the strike of the bedding in parts of Shenandoah Caverns.

Much of the cave lies in one horizontal plane, the main level seen by visitors, and in this there is evidence of a definite flow imposed by structure and topography. This might be considered a subwater-table stream plexus. It is 200 feet or more under the hilltop—too deep, one thinks, for such a stream beneath a peneplain. Entirely in harmony with other elements in the picture, however, is the idea of such a stream developing its main routes from selected passages in an earlier three-dimensional network while the North Fork was lowering the water table in the valley-floor peneplain. The Shenandoah's continued deepening has now drained the entire system for 250 feet below the hilltop.

Grand Caverns' phreatic features have been described (p. 704), but its position with reference to the valley-floor peneplain should

be noted. Grand Caverns lies in a narrow hill which here separates Middle River and South River, two branches of the South Fork of the Shenandoah, 10 miles southwest of the southern end of Massanutten Mountain. Valley-floor peneplain remnants in the vicinity are approximately 1,200 feet A.T., above which this hilltop rises nearly 200 feet. The vertical range in the cave is said to be about 150 feet, extending from river-level more than halfway to the summit of the hill. Thus the upper portions of the cave are a little higher than the peneplain trace. At the so-called "main level," the cave system is known to extend 1,000 feet along the strike.

Grand Caverns is one-seventh as long as the hill in which it occurs and is fairly centrally placed for all three dimensions of the hill. The hill is isolated down to the 1,160-foot contour, 60 feet above each of the adjacent rivers. The area of the hill thus bounded is only $2\frac{1}{4}$ square miles. Under these limitations nothing can be done with the vadose hypothesis at Grand Caverns except to ask that Middle River or South River have supplied the water. The cave answers that. It has none of the features left by streams entering a cavernous hillside, and it has many features that could not have survived such an experience. Grand Caverns, as a phreatic network cave with a large vertical element, must be older than the hill it is in, older than the valleys by which that hill has become isolated. It must date back at least to the valley-floor peneplain.

Luray Caverns is on the east side of Massanutten Mountain, at about mid-length of the mountain and about mid-width of the South Fork valley. The peneplain is readily recognized in this part of the valley at approximately 900 feet A.T. Standing on it are a few small residual hills, beneath one of which is Luray Caverns. A mile and a quarter from the cave, Shenandoah River has cut a narrow valley 200 feet below the peneplain level. The base of Cave Hill is 940 feet A.T., its summit is nearly 1,200. The cave's lowest level is 902 feet,[57] and its total vertical range of floors is only 31 feet. Thus, though Luray occurs beneath a monadnock on the valley-floor peneplain, it lies as low as the peneplain surface surrounding the hill.

Luray's remarkable wealth of dripstone is a handicap to the geolo-

[57] According to McGill, who is authority for most of the altitudes and vertical distances in the preceding discussions of Shenandoah Valley caves.

gist interested in cave origins. Too little original wall and ceiling are exposed, too much obstruction, subdivision, and even complete blockade of passages exists. Nevertheless, Luray's ground plan is clearly a phreatic network in the base of the hill—a network so extensive that, with Ruffner's Cave in the same hill, area of cave sys-

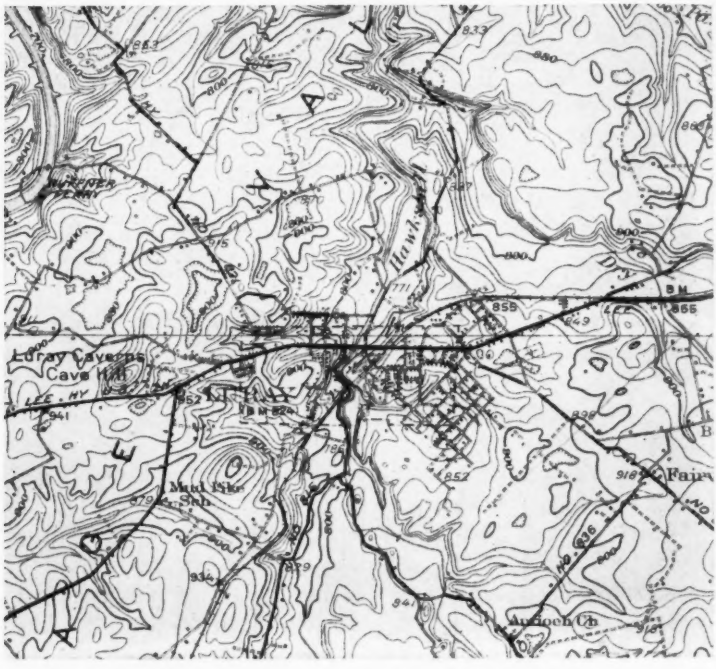


FIG. 52.—Vicinity of Luray Caverns, Va. Part of Stony Man quadrangle, United States Geological Survey.

tem is almost equal to area of hill. The network spreads as far across the strike of the Nittany dolomite as with it. Luray could never have been made under present conditions, if indeed it could have been made at the peneplain stage of the valley-floor cycle. More likely is it that Luray records ground-water work when, before the hill became isolated, the water table of this part of the valley was

higher than the highest solutional ceilings in the cavern. This might well have been some time in the maturity of the valley-floor cycle. No one, looking at McGill's map, can believe that very many of the blind ends shown are original. Most of them must be dripstone or hillside-waste blockades, and Luray of today must be only a small

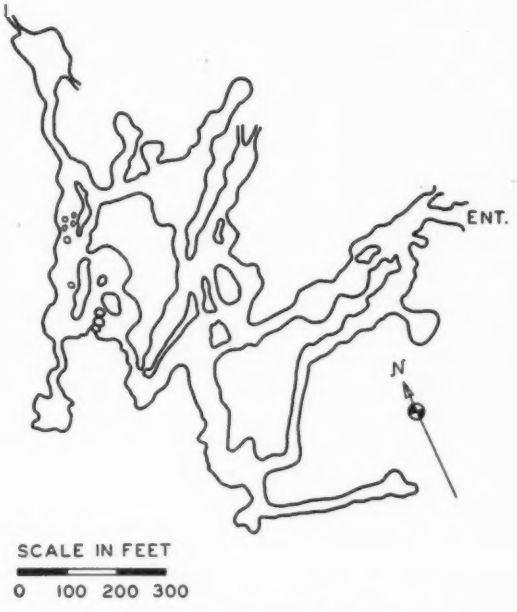


FIG. 53.—Map of Luray Caverns, Va. (after McGill)

surviving portion of a once linearly extensive subterranean drainage system. How deep was the cavern during the peneplain stage, that is, how deep is the existing fill? There is no evidence at Luray to tell. One can believe that if Massanutten, Endless, Melrose, Shenandoah, and Grand caverns lie below the peneplain level, much of Luray should also. It is only the survival of the monadnock that preserves the higher levels we see at Luray and of much of the fill that conceals lower levels. The other caves presumably had comparable higher levels earlier in the cycle and lost them during the final base-leveling.

PENNSYLVANIA CAVERNS

Stone uses the expression "the famous cave belt of Berks County"[58] (southeastern Pennsylvania), listing five caves in the belt. From his text, another five caves can be added if the "belt" is understood to be the southern part of the outcrop of the folded Martinsburg shale. Full width of outcrop is 7–10 miles, and its accordant hill and ridge tops are accepted as remnants of the dissected Harrisburg peneplain. Along the northwest side of the Martinsburg outcrop zone, the prominent ridge of Blue Mountain is held up by Medina and Oneida sandstones. Along the southeast side of the Martinsburg zone is a relatively narrow lowland belt on Beekmantown and Conococheague limestones, with hardly half the altitude of the Martinsburg area and with a much smoother surface.

Freeman Ward[59] has interpreted this low-lying limestone belt as the Somerville peneplain, reduced from the Harrisburg level almost wholly by solution while the relatively weak Martinsburg shale has been advanced by surface-stream dissection only to maturity in post-Harrisburg time. Two creeks, Moselem and Sacony, rising among the hills of quartzite and igneous rock southeast of this limestone belt, cross the limestone lowland in broad shallow valleys and enter the higher Martinsburg zone where their valleys abruptly become ten times as deep because of the superior altitude of this zone. Such drainage courses should be inheritances from the older peneplain.

Though Ward uses sink drainage of the limestone belt in his arguments, he says nothing about caves, either in the limestone members of the Martinsburg or in the rock beneath his Somerville tract. Stone's list of twenty limestone caves in Berks County appears to include only three or four in the low limestone belt, all the others being in the hilly Martinsburg shale area. Only one of these three or four (South Temple Cave) is more than a large cavity, and from the map and descriptions in Stone's bulletin one cannot safely conclude as to conditions of origin.

Of the caves in limestone members of the shale, only Crystal Cave near Kutztown has been seen by the writer. It is in a semi-isolated

[58] *Op. cit.*

[59] "The Role of Solution in Peneplanation," *Jour. Geol.*, Vol. XXXVIII (1930), pp. 262–70.

hill of the upland, a mile back from the rather abrupt descent southeastward to the low limestone belt. The summit is between 540 and 560 feet A.T. Within a radius of 4 miles of the cave there are but two 800-foot hilltops and most others are between 600 and 700 feet, lower values being nearer the cave. Drainage about this hill flows

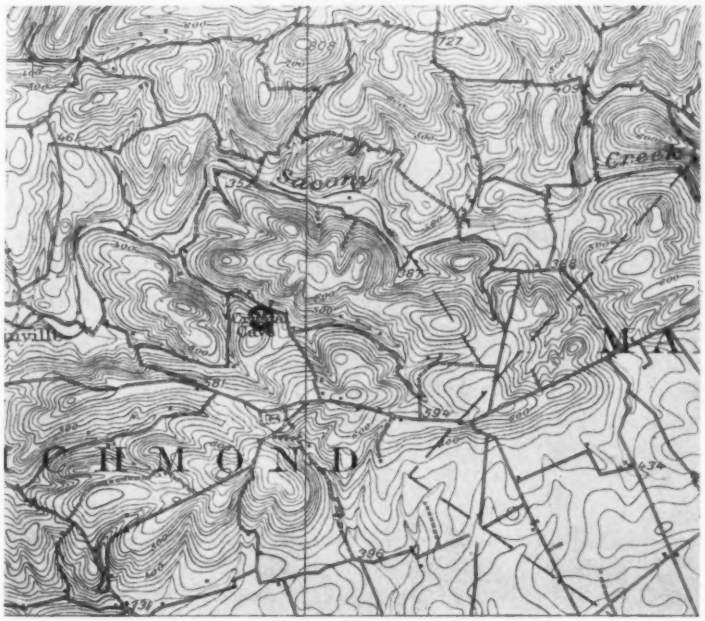


FIG. 54.—Vicinity of Crystal Cave, Kutztown, Pa. Part of Hamburg quadrangle, United States Geological Survey.

away from the limestone lowland, not toward it. A good guess at the altitude of the Harrisburg trace over the cave hill is 600 feet or a little more. The cave occurs about 20 feet below the hilltop.

A fault is crossed by the cave's largely horizontal chamber, on one side of which the strata dip 40°–60°, and on the other are nearly vertical. Cave elongation is essentially with the strike of the bedding, changing as that changes across the fault. So far as a solutional ceiling remains, it is marked by great irregular pockets made

under phreatic conditions. The near-horizontality of the capacious chamber, the (few) narrow, joint-determined, lateral chambers in the same plane, the ceiling pockets, the location in a hilltop, and the total absence of vadose-water records all seem to indicate that Crystal Cave dates back to an earlier cycle of erosion. If it does, it existed beneath the Harrisburg peneplain.[60]

Baker Caverns in Franklin County, south-central Pennsylvania, is an extensive network cave, elongated with the strike of steeply dipping Beekmantown, Stones River, and Chambersburg limestones. It lies but little below a broad plain well shown in the central part of the Mercersburg quadrangle map. Conochocheague Creek and its West Branch have trenched 100 feet into the plain, but their tributary heads must lengthen and multiply considerably before the tract will possess the stamp of maturity. It is an erosional surface, truncating five folded and faulted formations, which Stose[61] identifies as a part of the Somerville peneplain. Partially surrounded by this Somerville remnant and about 150 feet higher is a more dissected but still flat-topped area called by Stose a "part of the Harrisburg peneplain" and taken by Campbell as the type area for his proposed revision of terminology, whereby "Chambersburg" would be substituted for "Harrisburg."[62]

A limited area of numerous small sinks, all within less than a mile of the valley of Conococheague Creek, marks the region of the cave. That part of the plain overlying the cave has only minor sinks and is about 75 feet above the creek. The deepest sink, farther from the creek than the cave, reaches almost to creek level. The cave system itself is reported to have a vertical range of about 85 feet.

Entrance to Baker Caverns is from the side of a shallow sink where excavation in a small quarry years ago penetrated the cave. The roof here is only about 10 feet thick but the small sink never reached down to the cave. The main chamber can be traversed

[60] Stone's bulletin notes features of other caves in the Martinsburg shale of Berks County where labyrinthine networks, fragile projecting quartz veins, alteration of wall rock to a clayey consistency, and down-hanging ceiling blades suggest phreatic origin.

[61] "Mercersburg-Chambersburg Folio," *U.S. Geol. Surv. Folio 170* (1909).

[62] M. R. Campbell, "Chambersburg (Harrisburg) Peneplain in the Piedmont of Maryland and Pennsylvania," *Bull. Geol. Soc. Amer.*, Vol. XLIV (1933), pp. 553–73.

readily for all of 1,000 feet along the strike and has southward continuation for an unknown distance in four or five smaller passages similarly oriented. In this part of the cave the main chamber is

FIG. 55.—Vicinity of Baker Caverns, Williamson, Pa. Part of Mercersburg quadrangle, United States Geological Survey.

doubled, the eastern half lower than the western and both approximately coinciding with a thrust fault whose dip is eastward.

Small lateral passages abound, some very irregular in ground plan, others as straight as a taut string for 200 feet or more. The

straight ones follow bedding or joints or faults. Some are too tight for traversing, all are higher than wide. Some terminate abruptly with an end wall as steep as the sides. Some rejoin the main chamber, being parallel and close to it throughout their entire length.

Wall and ceiling pockets and joint-determined wall and ceiling cavities are fairly common, though much of the ceiling is a smooth truncation of the nearly vertical beds. Rock floor is exposed in some places and is as pockety and irregular as any part of the ceiling.

Superposed on walls and ceilings of the main chamber of this phreatic network are multitudes of flutes. In one inclined passage branching and descending northeastward off the lower main chamber, these flutes show unequivocally that the current flowed southwestward, *uphill* and *away from* the creek valley near by.

In contrast with this is a sharply cut small ravine in the cave floor which winds downgrade from the upper main to the lower main, and *toward* the creek valley.

In Baker Caverns, therefore, a phreatic network was first developed. Parts of this came to be used by a subwater-table stream which left flutes on ceilings and in one place flowed upgrade under hydrostatic pressure. A complete fill is not recorded. Subsequent to whatever filling episode occurred, the cave was drained by entrenching of Conococheague Creek and consequent lowering of the water table. Other caves reported from the vicinity are probably parts of the same system. The sinks are far younger than the system, are of the same age as the creek valley and the cave ravine, and occur only where cave chambers already existed beneath. Baker Caverns has the best shown and most nearly complete record, known to the writer, of a cavern system originally developed beneath and adapted to the topography of a peneplain, and modified during dissection of the peneplain first by a subwater-table stream and later by limited floor-stream drainage from local precipitation alone.

The nearness of Baker's main upper chamber to the surface of the plain seems to dispose of the possibility that it is an "imitation" two-cycle cave. The same may be said of some of the Shenandoah Valley caves described.

Other Pennsylvania caves in inclined beds undoubtedly show some of the items which have been read from Crystal and Baker. But

those seen by the writer do not have so clear a relationship to peneplain traces or are in unmapped or poorly mapped areas. The writer's argument for cavern development through the entire erosion cycle, continuing, as Davis believed, beneath the peneplain, is here closed. Should the dissected plain on the Guadalupe uplift prove to be a peneplain, Carlsbad and its associates will become examples. If the writer's argument for phreatic caverns beneath peneplains be sound, evidence and conclusion might well be reversed at Carlsbad. Great phreatic caverns may some day be added to the physiographer's evidences for uplifted peneplains. The Black Hills caves existed beneath an early Tertiary lowland erosion surface, according to Tullis and Gries.[63] The writer, having seen seven of these caves, concurs in the judgment that they are wholly phreatic in origin.

CAVES IN THE PHREATIC ZONE TODAY

Both Gardner and Swinnerton admit phreatic solution, but both minimize it. Gardner states that caverns encountered in well-drilling "in every case known in his personal experience, or from authority, ... have been at levels above the water table." But Moneymaker,[64] working with many open-cut excavations and several hundred thousand feet of core borings made by the Tennessee Valley Authority and with a great number of drill records and cores from other sources, has found thousands of solution cavities in various carbonate rocks below the water table and below the bedrock floor of the river. Some are more than 100 below, but they are most abundant at no great depth. Many are of cavern dimensions.

R. B. Campbell[65] reports that, in drilling a deep well in Florida, "three pronounced caverns" were encountered in a series of limestones, dolomites, and anhydrites at depths ranging between 2,846 and 2,986 feet. Their vertical dimensions were 18, 5, and 11 feet. "The entire section," he says, "was very porous, causing continuous loss of circulation."

At the Lower Canyon dam site on the Yellowstone River, 4 miles

[63] *Op. cit.*

[64] *Op. cit.*

[65] "Deep Test in Florida Everglades," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXIII (1939), pp. 1713–14.

southwest of Livingston, Montana, the War Department engineers encountered cavities in two of their drill holes into the Madison limestone. In an unpublished report kindly supplied by Lieutenant Colonel Helmer Swenholt, one cavity is described as 71 feet from ceiling to floor. Depth below bedrock floor of the river valley to this cavity is 69 feet.

Moneymaker found that "large cavities may be open or filled regardless of depth below the elevation of river bed, and this is equally true of small cavities. In a deep drill hole, which penetrates numerous cavities ranging in vertical thickness from a few inches to many feet, open and filled cavities commonly occur in irregularly alternating series, irrespective of either depth or size." A surprising feature of the fillings was the presence of gravel, water-worn cobbles, and even quartzite boulders up to a foot in diameter. Such coarse detritus apparently must record river-bed connection with largely vertical joint-plane openings, down which already worn material fell. The only statement in Moneymaker's paper suggesting the existence of subwater-table streams is that "where intersected by large holes or excavations, open or partly open channels discharged copious quantities of water."

In the Yellowstone exploratory drilling near Livingston, M. E. Kirby describes the 71-foot cavity as filled with horizontally bedded, whitish-gray clay and clayey sandstone, the clay containing microscopic shards of volcanic ash which must have been introduced from above, perhaps from the Bozeman lake beds.

The evidence from the Tennessee and Yellowstone valleys establishes the existence of cavities dissolved out, and some of them then filled up, while under wholly phreatic conditions.

CONCLUSION

Unquestionably there are caves whose history has been entirely vadose. But they are rare, so rare that, in the writer's opinion, only 3 of the 107 he has studied should be listed as unequivocally of such origin, with another 6 doubtfully so. The 3 are simple domepit cavities, their major dimensions vertical, the water entering fairly directly from a hillside to which it returns at a lower level. Davis repeatedly asked for branch-work ground plans as evidence for the

vadose origin of horizontal cave systems. He found but few and all were modifications of older network ground plans. In this respect, the writer's field search has duplicated Davis' search of the literature.[66] Horizontally elongated caverns lacking any kind of phreatic record must be very rare.

Vadose traits, identified from the work of living cave streams, are almost all superimposed on older chambers or systems of chambers which the streams are destroying and obviously could not have made. Caves carrying this record of two epochs are most common. In the writer's list, 49 caves belong to this class while 44 are interpreted as wholly phreatic in origin. In 11 caves studied, the evidence collected is insufficient for judgment.

There are several aspects of the cave problem, as outlined by Davis, not treated here. On the topics herein discussed, there are many unanswered questions in the writer's notes, some of which appear in this paper. Doubtless there are interpretations herein which will be unacceptable to some. Surely not all the significant caves have been seen and not all the significant criteria have been recognized. Even if Davis' thesis should have been established to the reader's satisfaction, much more field work is needed on the subject of limestone caverns.

ACKNOWLEDGMENTS.—Acknowledgment is gratefully made to the many cave owners, managers, and guides whose helpfulness has materially furthered the field study, to many students who surveyed and mapped some of the caves herein described, and to Dr. A. C. Swinnerton, who participated in a field conference with the writer at Mammoth Cave and who critically read the manuscript of this paper.

CAVES MENTIONED IN THIS PAPER

Baker Caverns, near Williamson, Pa.
Bat Cave, near Mammoth Cave, Ky.
Battlefield-Crystal Cave, Strasburg, Va.
Big Hurricane Cave, near Western Springs, Ark.
Big Mouth Cave, near Harrisonburg, Va.

[66] Hidden River Cave, Kentucky, with a good stream in it, may be an exception. Too little was seen by the writer to justify a definite conclusion, but Pohl in a personal communication says this stream has been followed for about 27 miles underground and has nineteen subterranean tributaries.

Cameron Cave, near Hannibal, Mo.
Carlsbad Cavern, Carlsbad National Park, N.M.
Cathedral Cave, near Leasburg, Mo.
Cave Hill Cave, Gallatin Co., Ill.
Cave-in-Rock, Cave-in-Rock, Ill.
Cave of the Mounds, near Blue Mounds, Wis.
Cave of the Winds, near Manitou Springs, Colo.
Colossal Cave, near Mammoth Cave, Ky.
Craigshead Caverns, near Sweetwater, Tenn.
Crystal Cave, near Kutztown, Pa.
Crystal Lake Cave, near Dubuque, Iowa
Cudjo's Cave, Cumberland Gap, Va.

Dixie Caverns, near Salem, Va.
Dossey (or Dorsey) Cave, near Mammoth Cave, Ky.

Eagle Cave, near Muscoda, Wis.
Endless Caverns, near New Market, Va.

Floyd Collins Crystal Cave, near Mammoth Cave, Ky.

Grand Caverns, Grottoes, Va.
Great Onyx Cave, near Mammoth Cave, Ky.
Griffith Cave, Hardin Co., Ill.

Hidden River Cave, Horse Cave, Ky.
Highland Cave, near Eureka Springs, Ark.
Hipple Cave, near Waterside, Pa.
Historic Indian Cave, near Franklinville, Pa.
Horseshoe Bay Cave, 4 miles south of Egg Harbor, Wis.

Indian Cave, near New Market, Tenn.

Lookout Mountain Cave, Chattanooga, Tenn.
Lost Cave, Hellertown, Pa.
Lost River Cave, near Bowling Green, Ky.
Luray Caverns, Luray, Va.

Mammoth Cave, Ky.
Mammoth Onyx Cave, near Horse Cave, Ky.
Mark Twain Cave, near Hannibal, Mo.
Massanutten Caverns, near Harrisonburg, Va.
Melrose (Virginia) Caverns, near Harrisonburg, Va.
Meramec Cave, near Stanton, Mo.
Missouri Caverns, near Leasburg, Mo.
Mushroom Cave, Meramec State Forest, Mo.
Mystery Cave, Lanagan, Mo.

Niagara Cave, near Harmony, Minn.

Ohio Caverns, near West Liberty, Ohio
Onondaga Cave, near Leasburg, Mo.

Pokerville Cave, near Blue Mounds, Wis.

Round Spring Cavern, 10 miles north of Eminence, Mo.
Ruffner's Cave, Luray, Va.
Running Branch Cave, near Mammoth Cave, Ky.

Salts Cave, near Mammoth Cave, Ky.
Seawra Cave, 12 miles northeast of Lewiston, Pa.
Shenandoah Caverns, Shenandoah, Va.
Shetlerville Cave, Hardin Co., Ill.
Slaughter Canyon Cavern, near Carlsbad Caverns, N.M.
Smittle Cave, 5 miles north of Grove Springs, Mo.
South Temple Cave, near Reading, Pa.
Stage Barn Cavern, near Piedmont, S.D.

Trinkle Cave, near Hardinsburg, Ind.
Truitt's Cave, Lanagan, Mo.

Virginia (Melrose) Caverns, near Harrisonburg, Va.

Wesley Chapel Gulf Cave, Orange Co., Ind.
Wildcat Cave, 6 miles west of Rapid City, S.D.
Wilson Cave, near Mammoth Cave, Ky.
Wind Cave, Wind Cave National Park, S.D.
Wonder Cave, 2½ miles northeast of Decorah, Iowa
Wonder Cave, near Monteagle, Tenn.
Wonderland Caverns, Mann's Choice, Pa.
Wyandotte Cave, Wyandotte, Ind.

Zane Caverns, near Bellefontaine, Ohio